Experimental Methods in Top Quark Physics

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TOPQUARK2006
University of Coimbra, Portugal
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Top Experimental Characteristics

Need entire detector

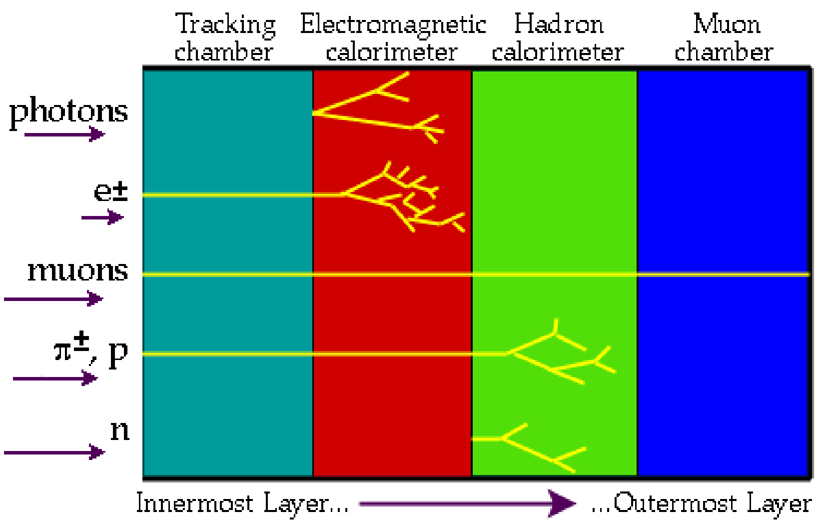
Electron id

Muon id

Jets

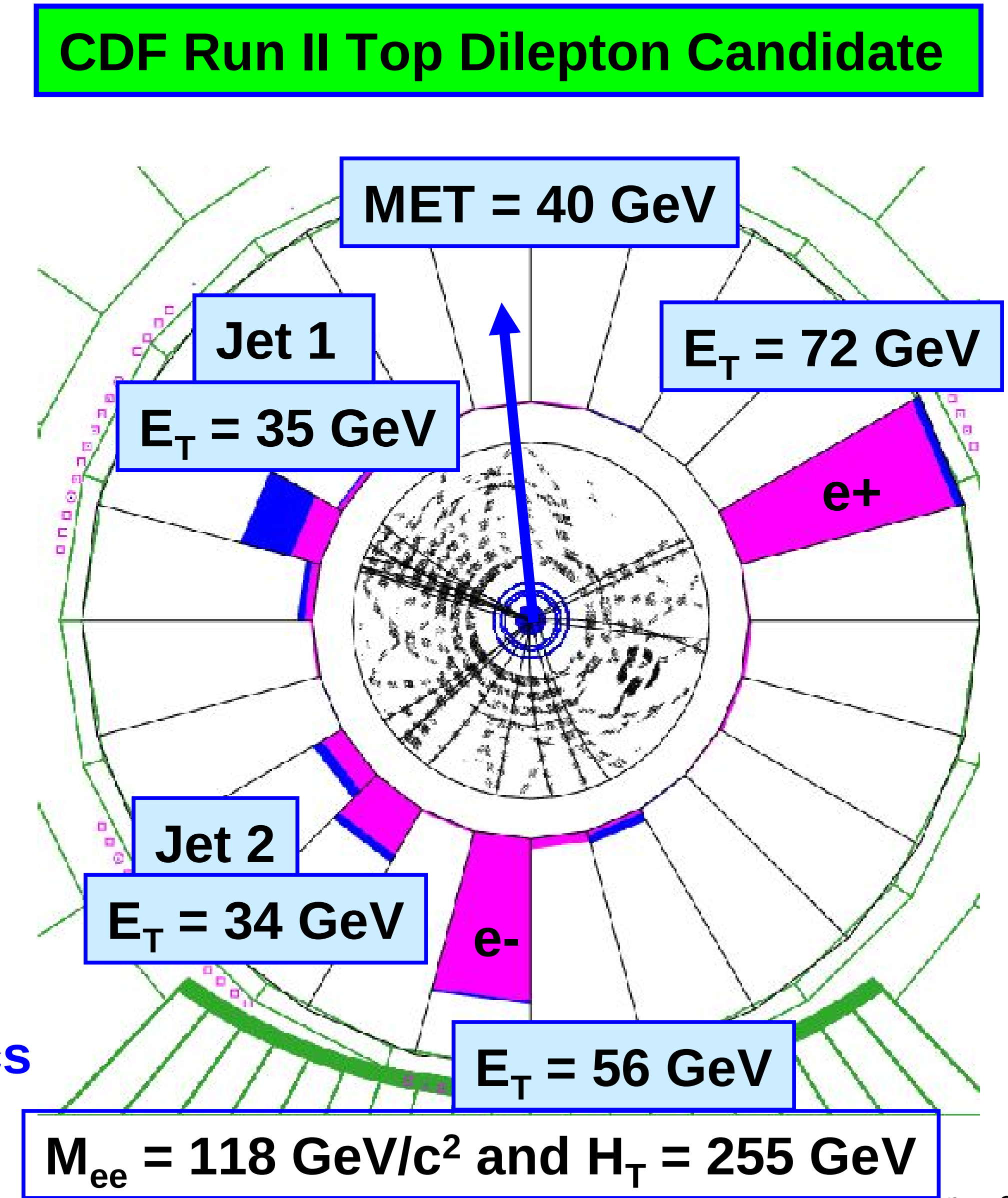
Missing transverse energy (MET)

b-tagging



Need advanced techniques

Detect subtle effects from physics beyond the standard model



Outline

Physics at hadron collider
Trigger
Leptons
Luminosity

Modelling
Top Pair Production
Dominant Backgrounds

Kinematics
Top Mass
Jet Energy Scale

b-tagging
W+heavy flavour
Single top

Multivariate techniques
Blind analysis
Top tools

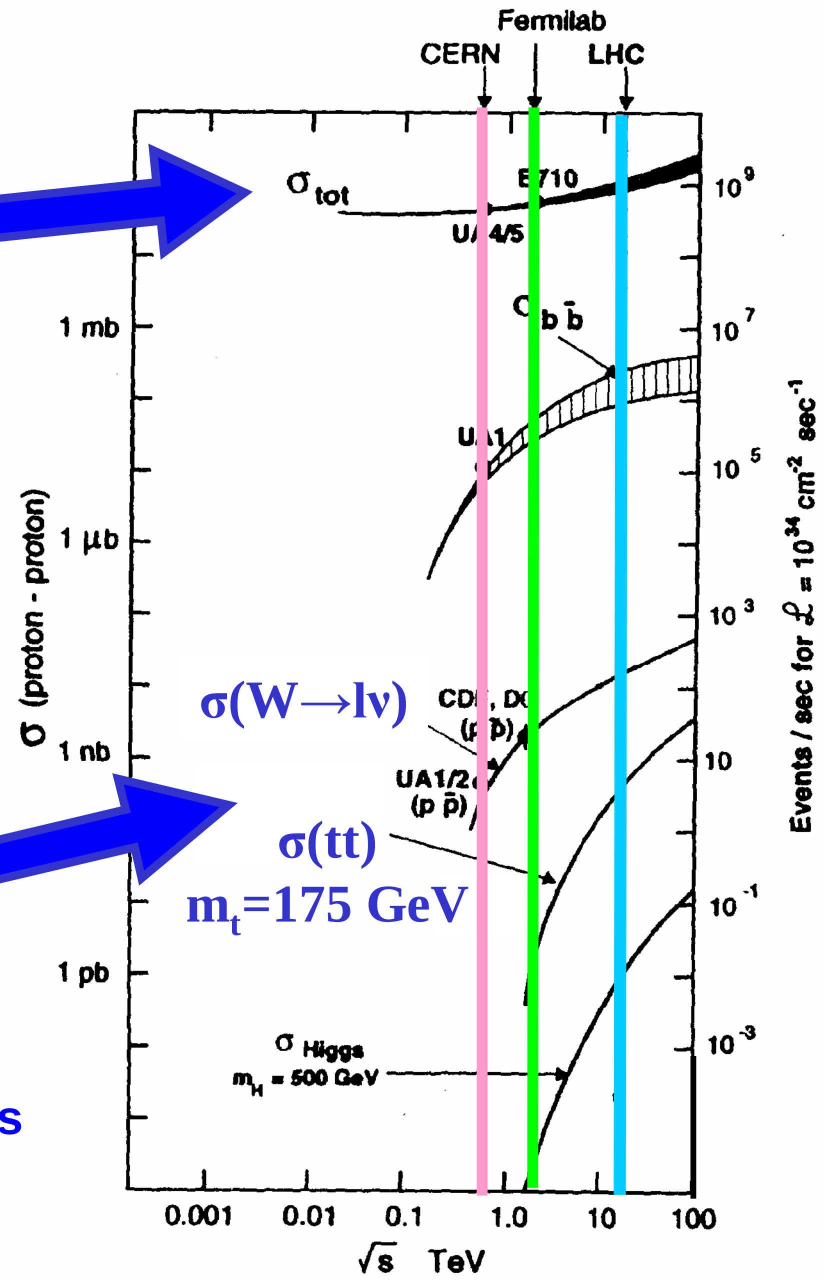
Physics at a hadron collider is like…

…drinking from a fire-hose

- Collision rate huge
  - Tevatron – every 396 ns
  - LHC – every 25 ns
- Total cross section huge
  - 2-3 interactions per collision
    - Tevatron L $=10^{32}\ cm^{-2}s^{-1}$
    - LHC initial L $=10^{33}\ cm^{-2}s^{-1}$
  - 20 interactions per collision
    - LHC design L $=10^{34}\ cm^{-2}s^{-1}$

…panning for gold

- W, Z, top are relatively rare
  - Need high luminosity
  - Trigger is crucial
    - Distinguish from jets, jets, and more jets by using high p_T leptons



Top Triggers

- **High p_T electron or muon**
  - W, Z
  - Top Dilepton
  - Top Lepton+Jets
  - Single Top
- **≥4 high E_T jets and high event E_T**
  - Top All-hadronic
  - Top Tau+Jets
- **Back-up triggers**
  - Measure signal L1, L2, L3 trigger efficiencies
  - Calibrate b-tag efficiency
  - Calibrate jet energy scale

- **Well-understood trigger is crucial!**
  - Did all the triggers that should have fired for an event actually fire? If not, why not?
  - Is the trigger efficiency flat in p_T?
  - Is the trigger efficiency flat in azimuth and pseudo-rapidity?
  - Changes in operation conditions can affect trigger performance: monitor stability over time
  - How fast does the trigger rate grow with instantaneous luminosity?
  - How much back-up trigger data needed at highest luminosities?

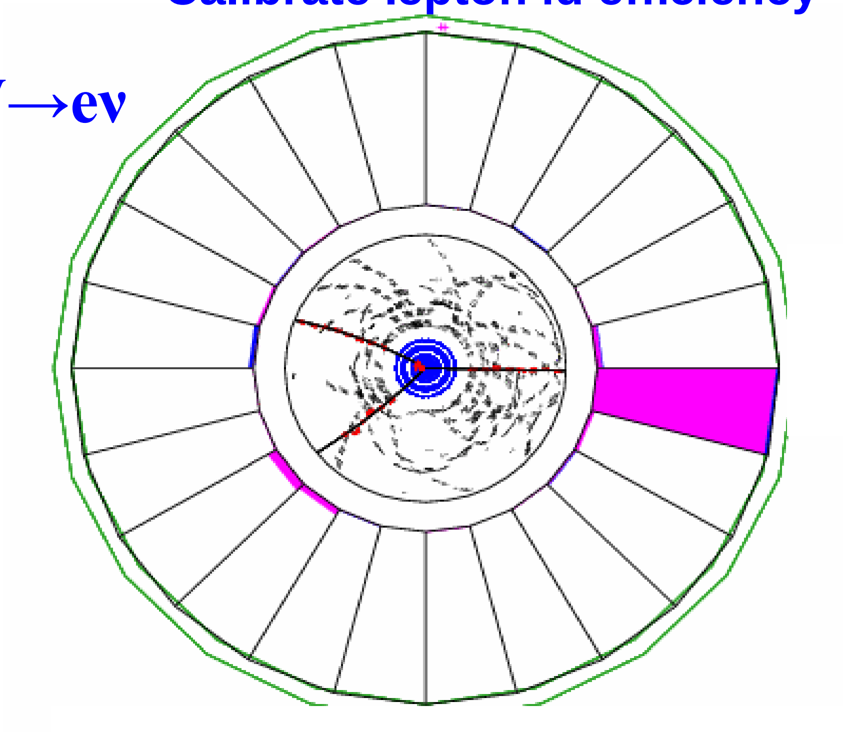
Lepton identification

W and Z production provide
Clean Isolated Leptons:

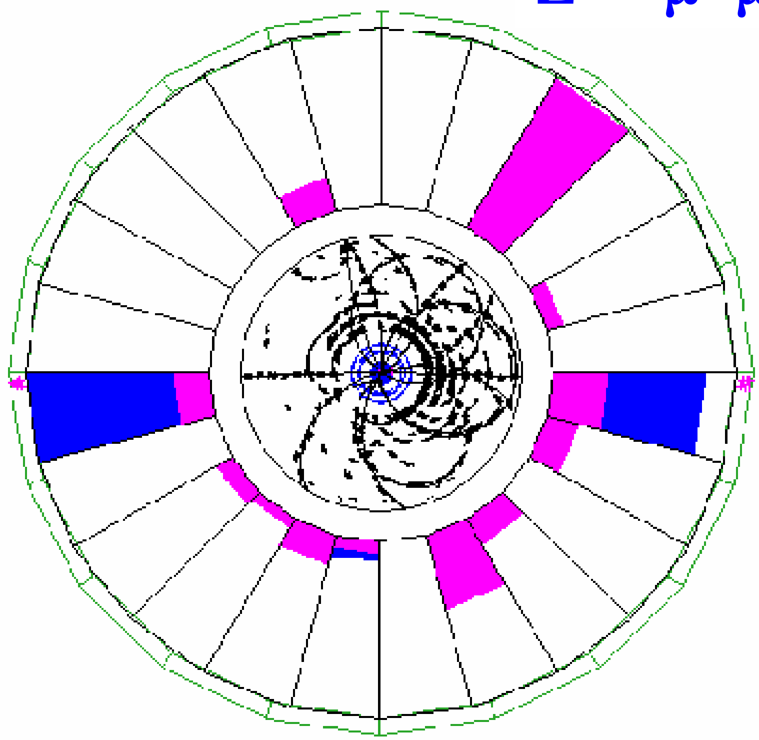
Validate simulation of lepton id observables

Calibrate lepton id efficiency

$W \rightarrow e\nu$



$Z^0 \rightarrow \mu^+ \mu^-$



A little too clean though…

Top events have more jets, so leptons less isolated

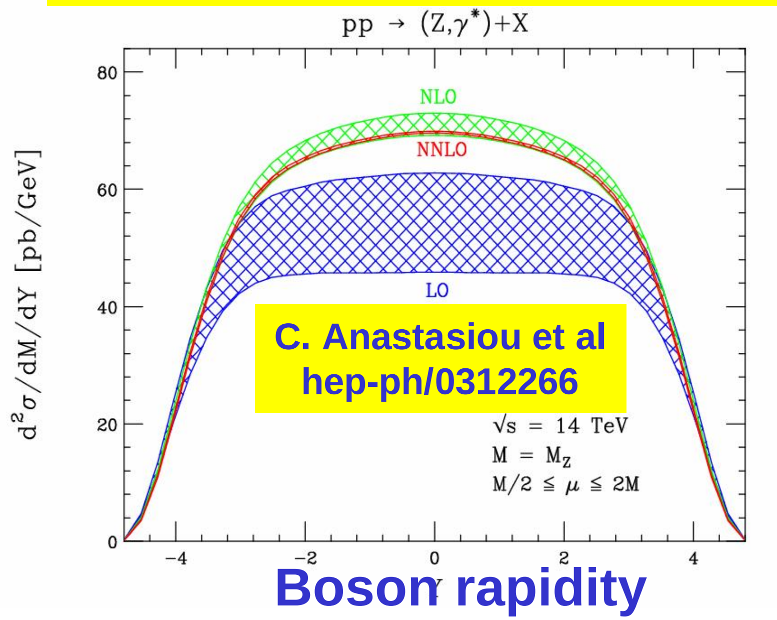
Compare data and simulation as a function of lepton-jet separation or energy in a cone around the lepton

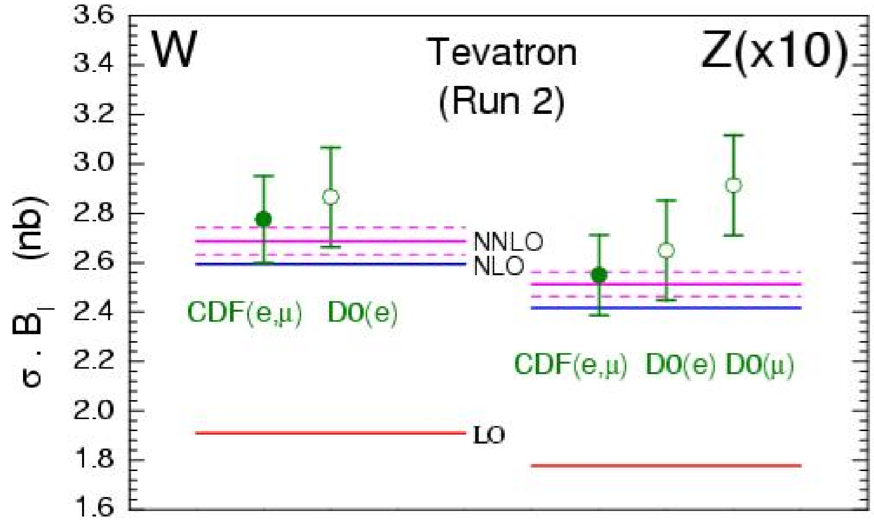
This was a 5% systematic, now 2%

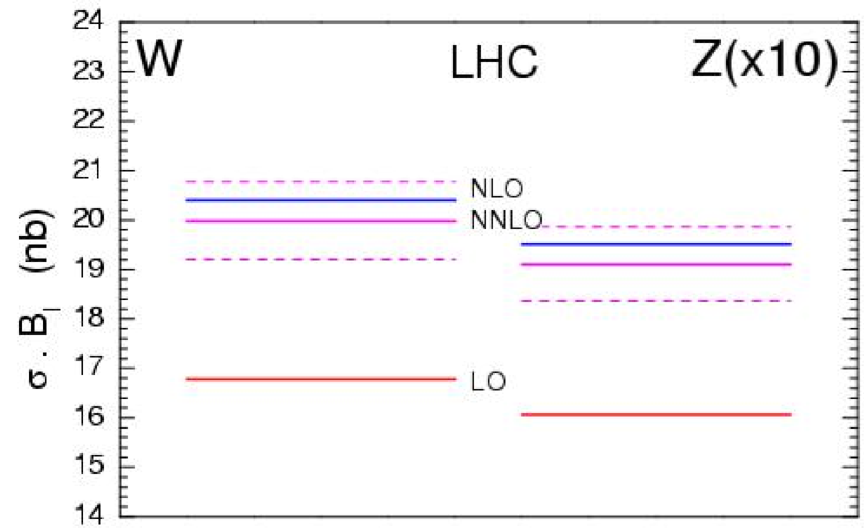
Measure luminosity with W and Z at LHC?

- **Tevatron: precision xs measurement limited by independent determination of luminosity**
  - **Acceptance theory uncertainty 2%**
  - **Experimental uncertainty 2%**
  - **Luminosity uncertainty 6%**
- **LHC: instead use good prediction from NNLO and higher rate of W and Z to monitor luminosity**

S. Frixione, M. Mangano hep-ph/0405130







partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

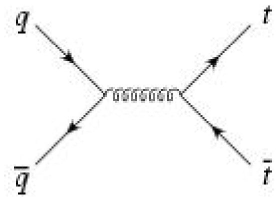
From W.J. Stirling

Top Quark Pair Production & Decay

Produce in pairs via strong interaction

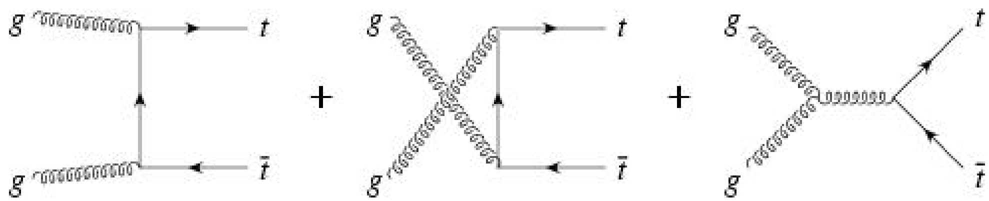
Cacciari et al.
JHEP 0404:068 (2004)
Kidonakis & Vogt
PRD 68 114014 (2003)

At $\sqrt{s}$=1.96 TeV:
85% $q\bar{q}$
15% gg



m_t (GeV/c^2)	σ(pb) Min	Central	Max
170	6.8	7.8	8.7
175	5.8	6.7	7.4

At $\sqrt{s}$=14 TeV:
10% $q\bar{q}$
90% gg
σ = 833 ± 100 pb

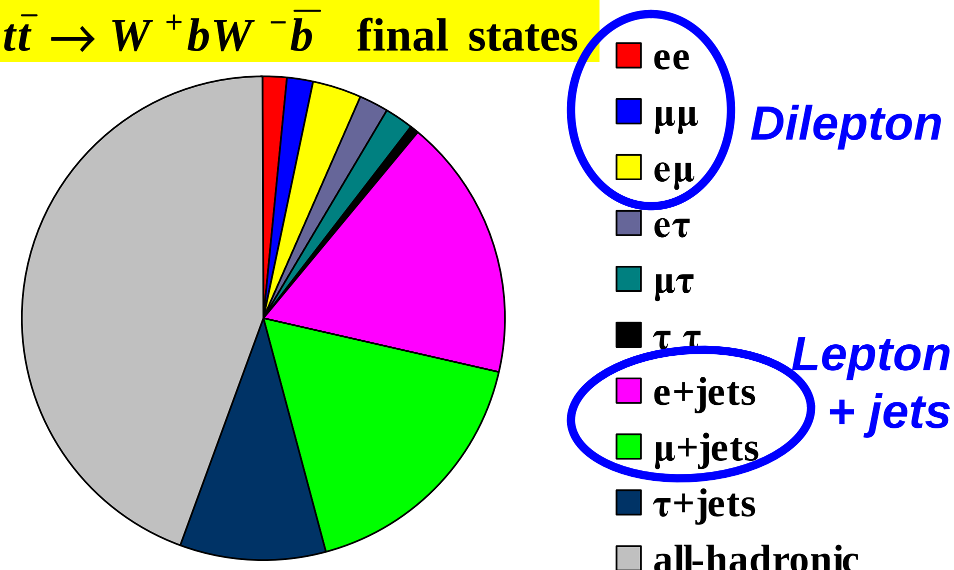


Decay via electroweak interaction $t \rightarrow W^+ b$

t→Wb has ~100% branching ratio
Width ~1.5 GeV so lifetime 10^{-25}s
No top mesons or baryons!

Final state characterized by
number and type of charged leptons
from decay of W^+ and W^- bosons

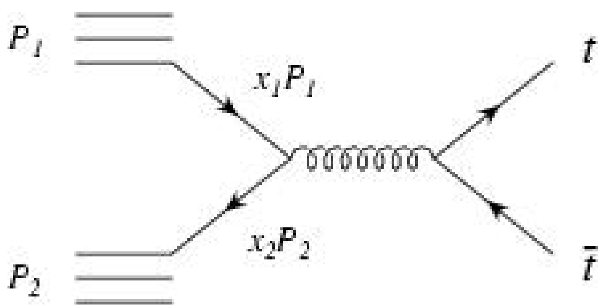
$t\bar{t} \rightarrow W^+ b W^- \bar{b}$ final states



(Note e includes $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ and μ includes $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$)

Top Quark Pair Production

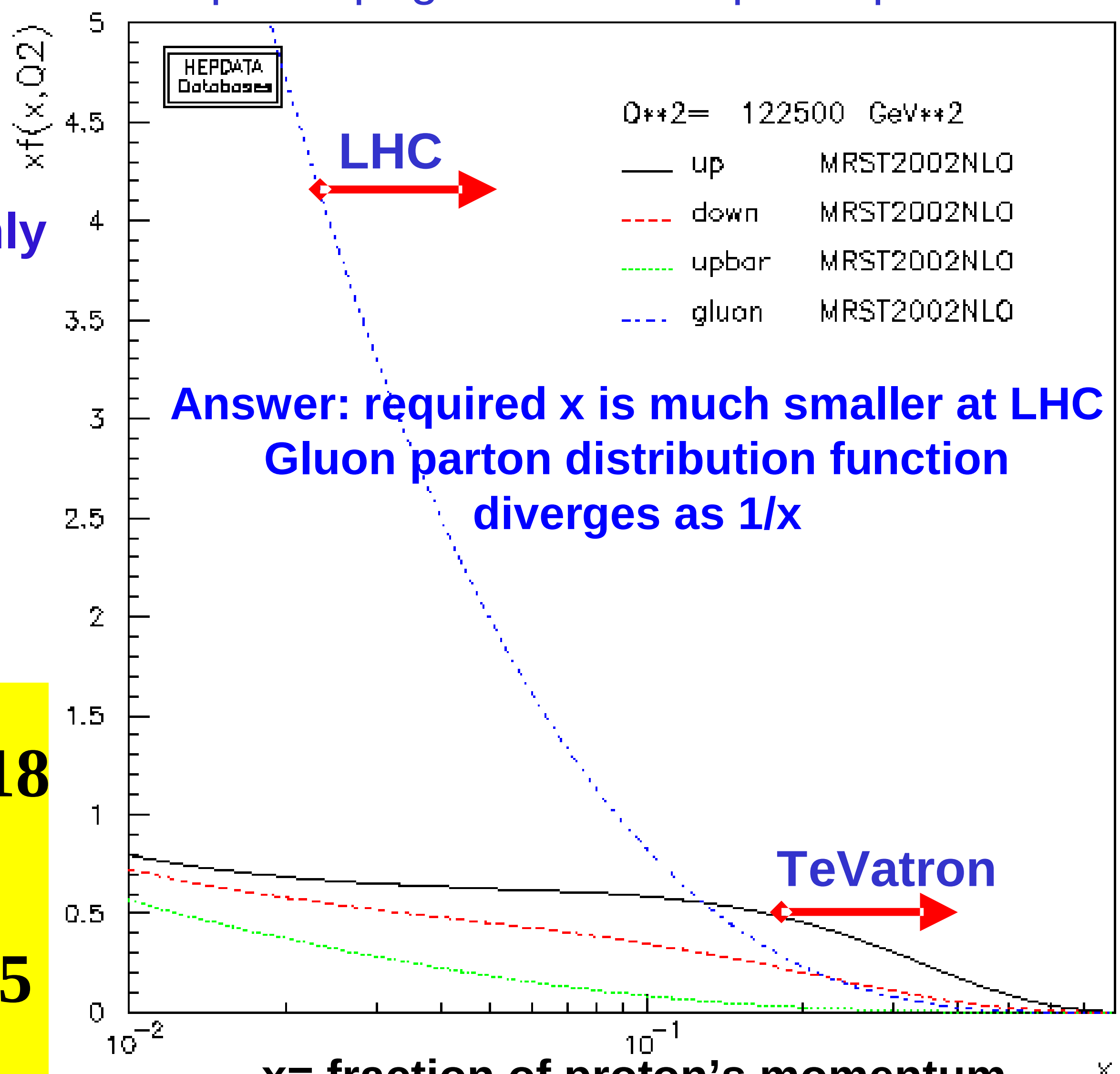
- Why is $q\bar{q}$ annihilation dominant at the Tevatron but gg fusion at LHC?
- Why does cross section increase 100 times for only 7 times increase in beam energy?



$$x \geq \frac{m_t}{E_{\text{beam}} = 0.98\,\text{TeV}} = 0.18$$

$$x \geq \frac{m_t}{E_{\text{beam}} = 7\,\text{TeV}} = 0.025$$

http://durpdg.dur.ac.uk/hepdata/pdf3.html



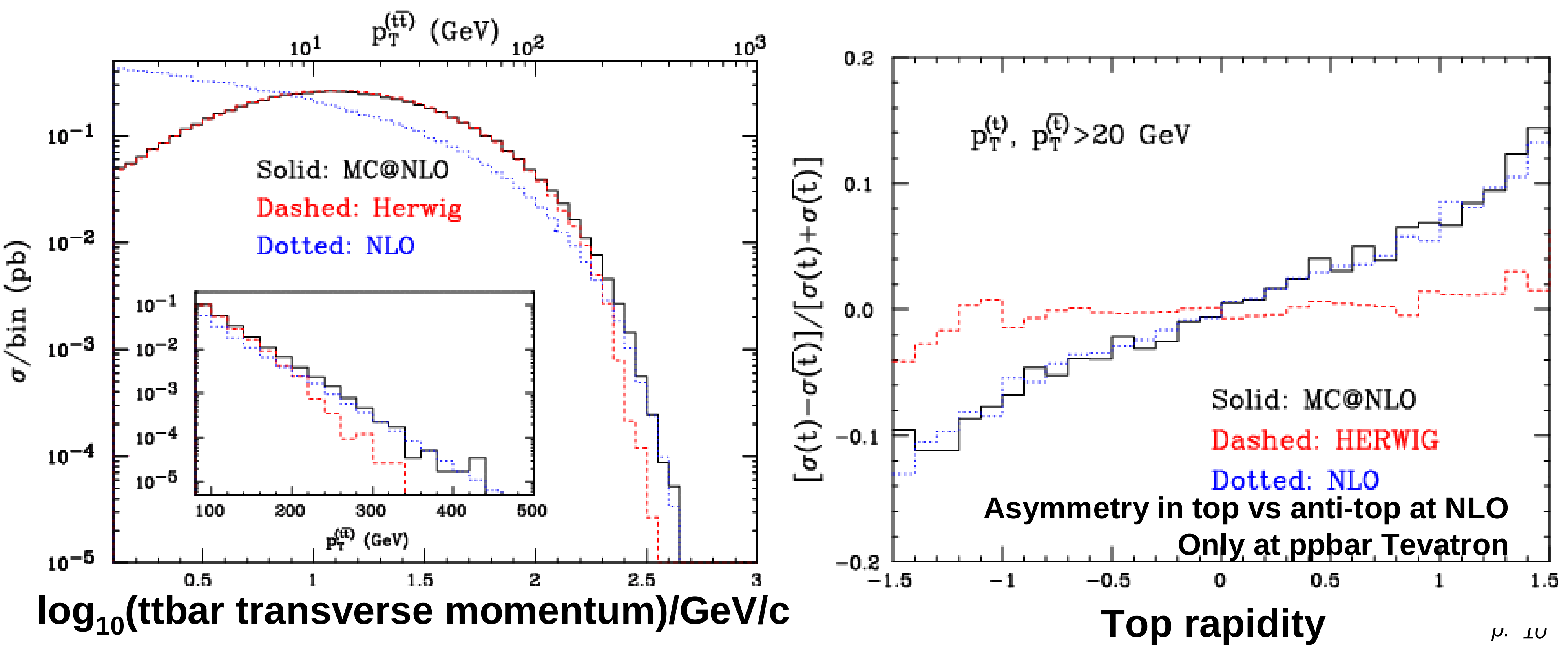
x= fraction of proton's momentum carried by parton

Kinematic Modelling of top pairs

- PYTHIA/HERWIG
  - Yesterday, you saw good agreement with Tevatron data!
- MC@NLO available too

S. Frixione, P. Nason, B. Webber hep-ph/0305252

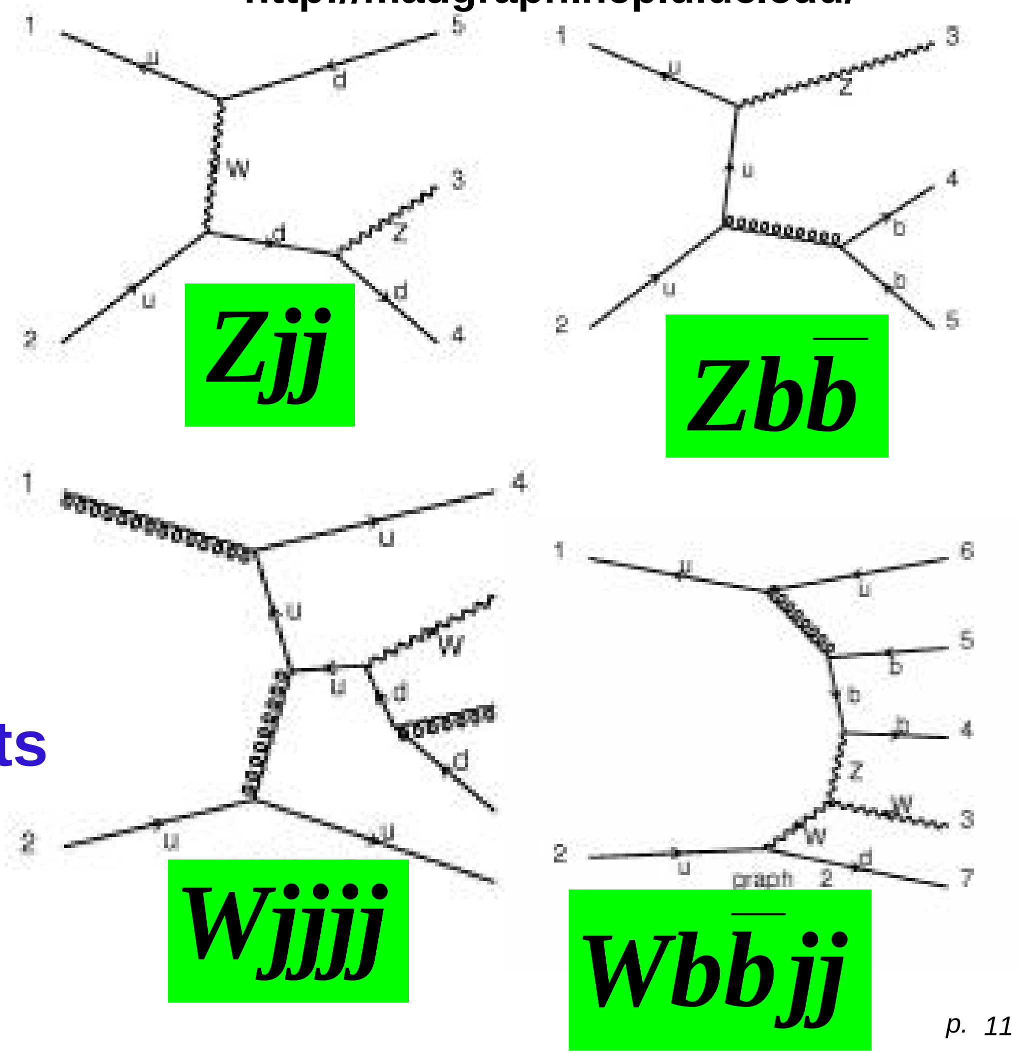
  - Next-to-Leading Order (NLO) in QCD
  - Event generator - can run detector simulation and reconstruction
  - Agrees with NLO at high p_T and with MC at low p_T



Backgrounds

- Many standard model processes have the same final state as top pair production
  - Dilepton final state
    - Z+jets
    - WW/WZ/ZZ+jets
    - W+jets + fake lepton
  - Lepton+jets final state
    - W+jets
    - Z+jets (miss one lepton)
    - WW/WZ/ZZ+jets
    - multijets+fake lepton
- NB: Only few % of W/Z+jets have any heavy flavour in the final state

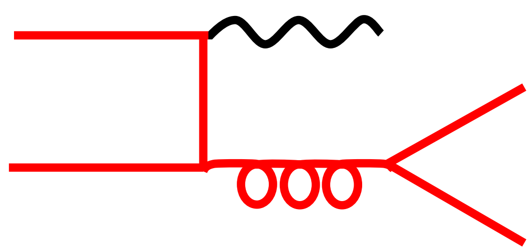
Some of the hundreds of Feynman diagrams
MADGRAPH
F. Maltoni and T. Stelzer
JHEP 0302:027,2003
http://madgraph.hep.uiuc.edu/



Main backgrounds: W+jets and Z+jets

- **Next-to-Leading Order (NLO) in QCD for W or Z with up to 2 partons**
  - **MCFM http://mcfm.fnal.gov/ by John Campbell and Keith Ellis**
    - **Next-to-Leading Order rate more stable**
    - **Calculates any infra-red safe kinematic variable at NLO**
- **Leading Order (LO) in QCD for W/Z with up to 6 partons**
  - **ALPGEN http://mlm.home.cern.ch/mlm/alpgen/ by Mangano et al.**
    - **Typical uncertainty of about 50% from choice of scale to evaluate α_s**

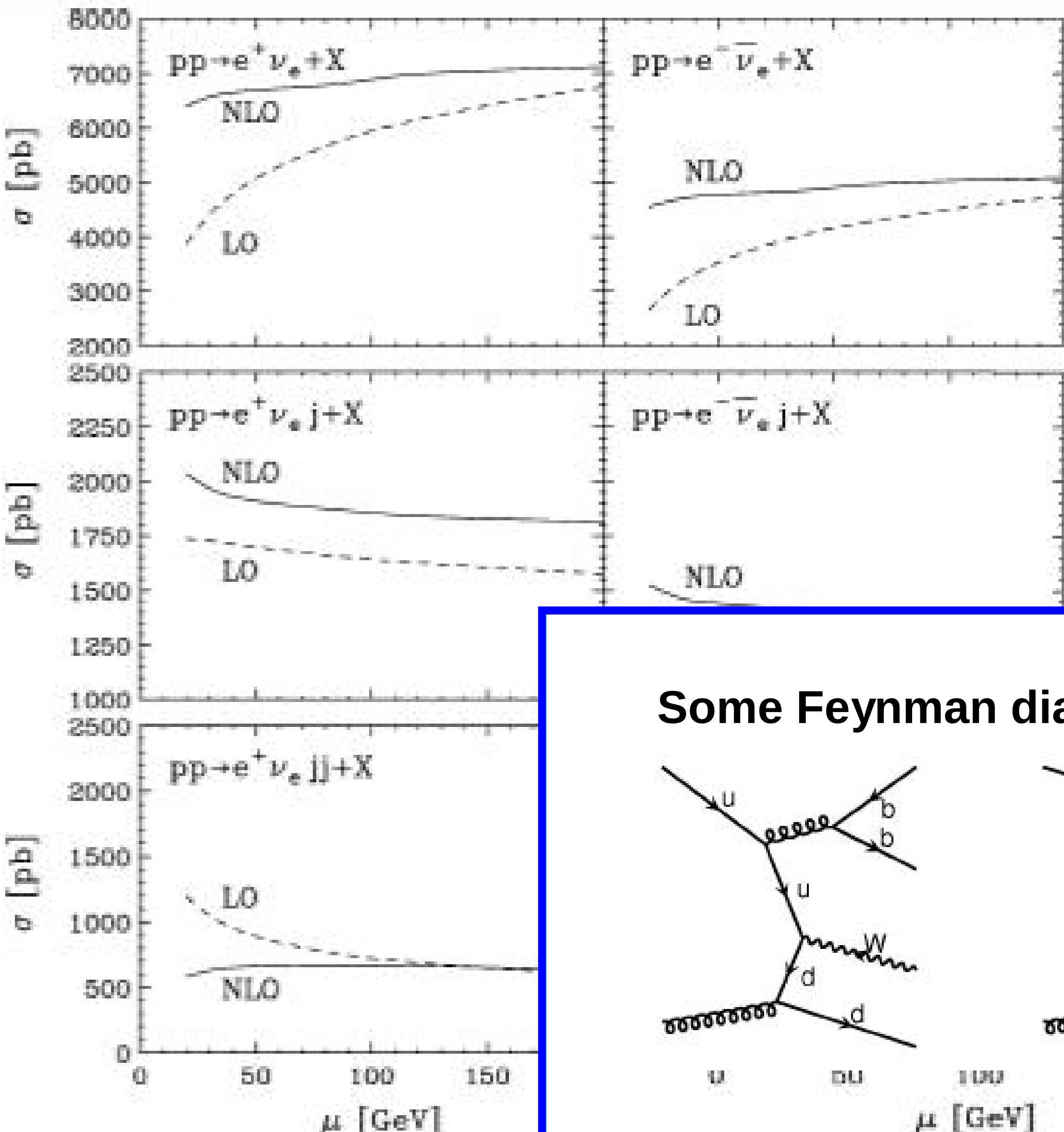
Leading Order Matrix Element
ALPGEN or MADGRAPH



Good: Hard/wide-angle radiation
Bad: Soft/collinear radiation (ME diverges)

W+jet and $Wb\bar{b}$ production rates at NLO

NLO prediction much less scale-dependent than LO



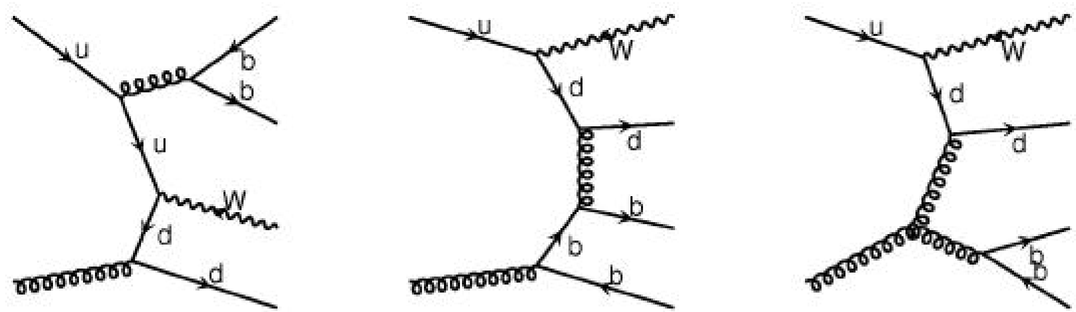
LHC $\sqrt{s}$=14 TeV
lepton p_T>15GeV |η|<2.4
Jet p_T>20 GeV, |η|<4.5, b-jets |η|<2.5

MCFM hep-ph/0308195
Campbell, Ellis, Rainwater

$Wb\bar{b} < 1\%$ of Wjj

- **Note charge conservation allows only $q\bar{q}$ initial states at LO. NLO increase due to qg initial states and large gluon luminosity at LHC**

Some Feynman diagrams at NLO for $qg \to Wb\bar{b}$



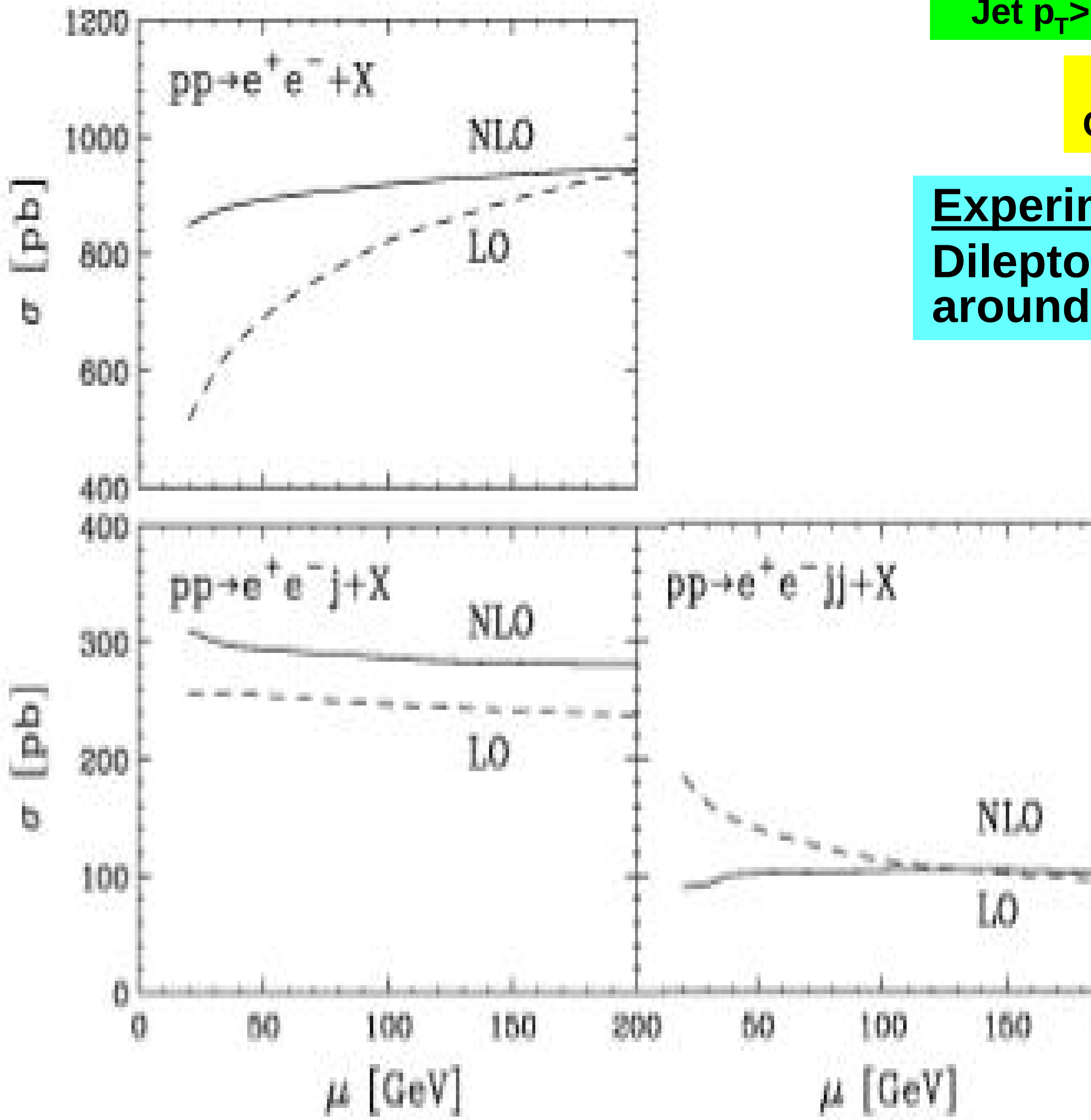
Z+jet production rates at NLO

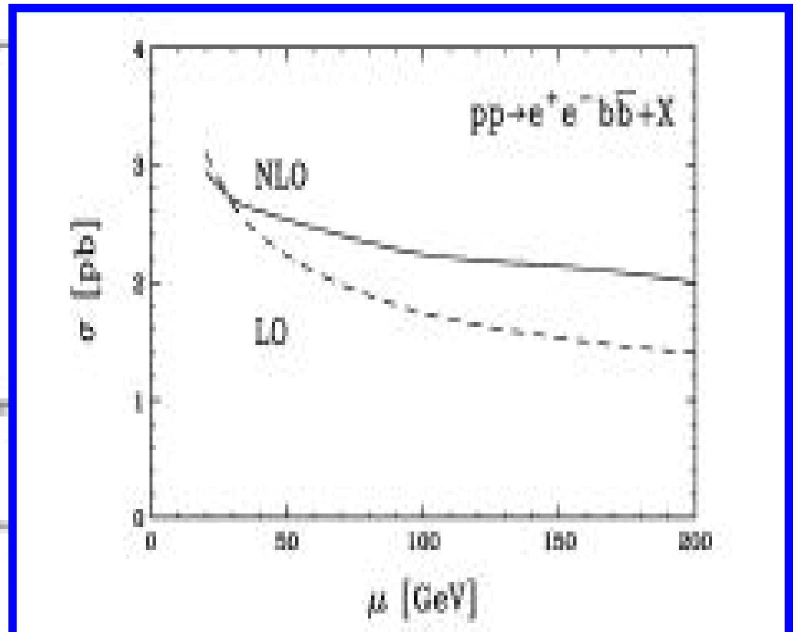
LHC $\sqrt{s}$=14 TeV
lepton p_T>15GeV |η|<2.4
Jet p_T>20 GeV, |η|<4.5, b-jets |η<2.5

MCFM hep-ph/0308195
Campbell, Ellis, Rainwater

<u>Experiments can reject most Zjj:</u>
Dilepton invariant mass peaks around Z mass and MET is low

$Zb\bar{b} \approx$ 2% of Zjj





Main backgrounds: W+jets and Z+jets

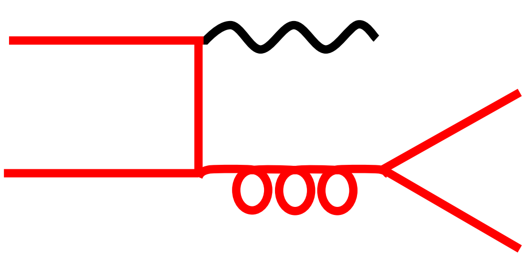
- Next-to-Leading Order (NLO) in QCD for W or Z with up to 2 partons
  - MCFM http://mcfm.fnal.gov/ by John Campbell and Keith Ellis
    - Next-to-Leading Order rate more stable
    - Calculates any infra-red safe kinematic variable at NLO
- Leading Order (LO) in QCD for W/Z with up to 6 partons
  - ALPGEN http://mlm.home.cern.ch/mlm/alpgen/ by Mangano et al.
    - Typical uncertainty of about 50% from choice of scale to evaluate α_s
    - Apply parton shower to fill in soft/collinear radiation
    - Event generator – can run detector simulation and reconstruction on output
  - Important to avoid double-counting or under-counting of radiation between matrix element and parton shower
    - CKKW hep-ph/0109231, Mrenna/Richardson hep-ph/0312274, Krauss hep-ph/0407365, ALPGEN http://mlm.home.cern.ch/mlm/talks/lund-alpgen.pdf

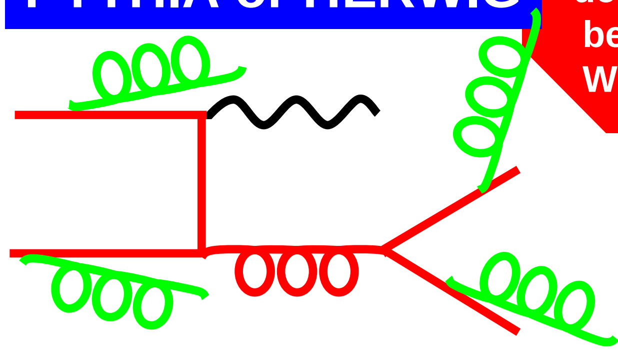
Leading Order Matrix Element
ALPGEN or MADGRAPH

+

Parton Shower MC
PYTHIA or HERWIG

STOP!
Hard radiation described better by W+3p ME



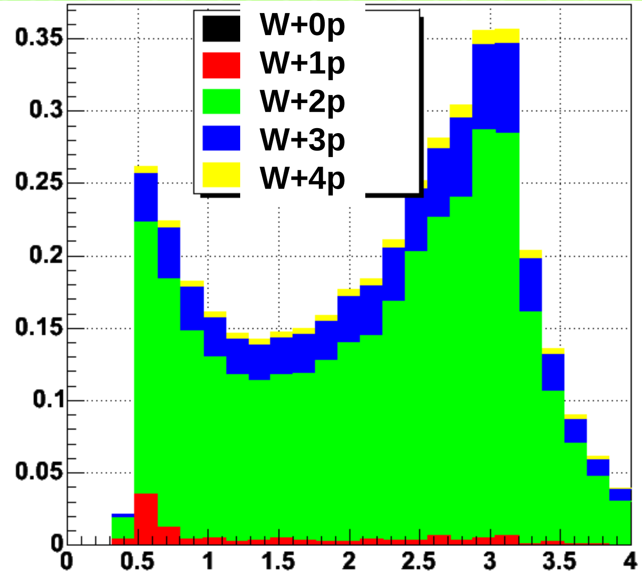


Good: Hard/wide-angle radiation
Bad: Soft/collinear radiation (ME diverges)

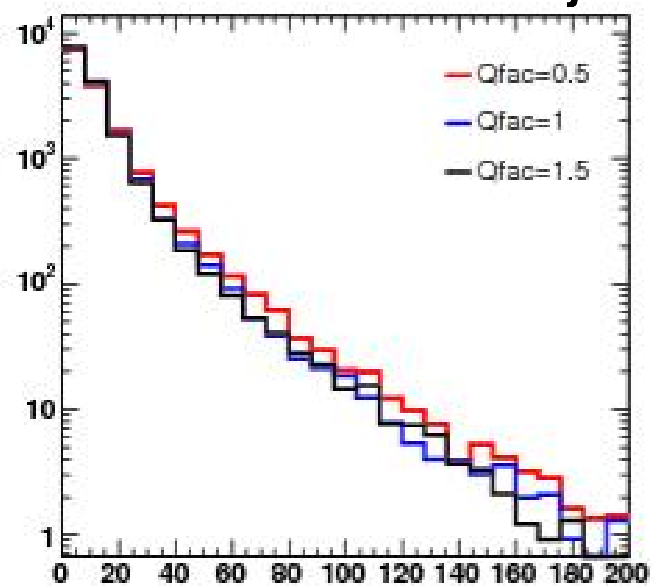
Bad: Hard/wide-angle radiation
Good: Soft/collinear radiation

Kinematic Modelling of W+jets & Z+jets

- **Example: W with 2 high p_T jets**
  - **Generate matched ALPGEN+HERWIG samples for each of W+0p, W+1p, W+2p, W+3p, and W+4p matrix elements**
  - **Add samples in proportion to their ALPGEN+HERWIG cross-section**
    - **W+1 parton: parton shower fills in with mostly collinear radiation**
    - **W+2 parton: dominant contribution**
    - **W+3 parton: significant contribution**
    - **W+4 parton: small contribution**
- **Example: Z+jets**
  - **Generate matched ALPGEN+HERWIG samples for Z+0p, Z+1p, Z+2p, Z+3p**
  - **Add samples in proportion to their ALPGEN+HERWIG cross-section**
  - **Some distributions dependent on Q^2 scale**
    - **Possible to tune Q^2 scale to match data?**
- **In progress: Comparisons with data**



Minimum ΔR between 2 jets

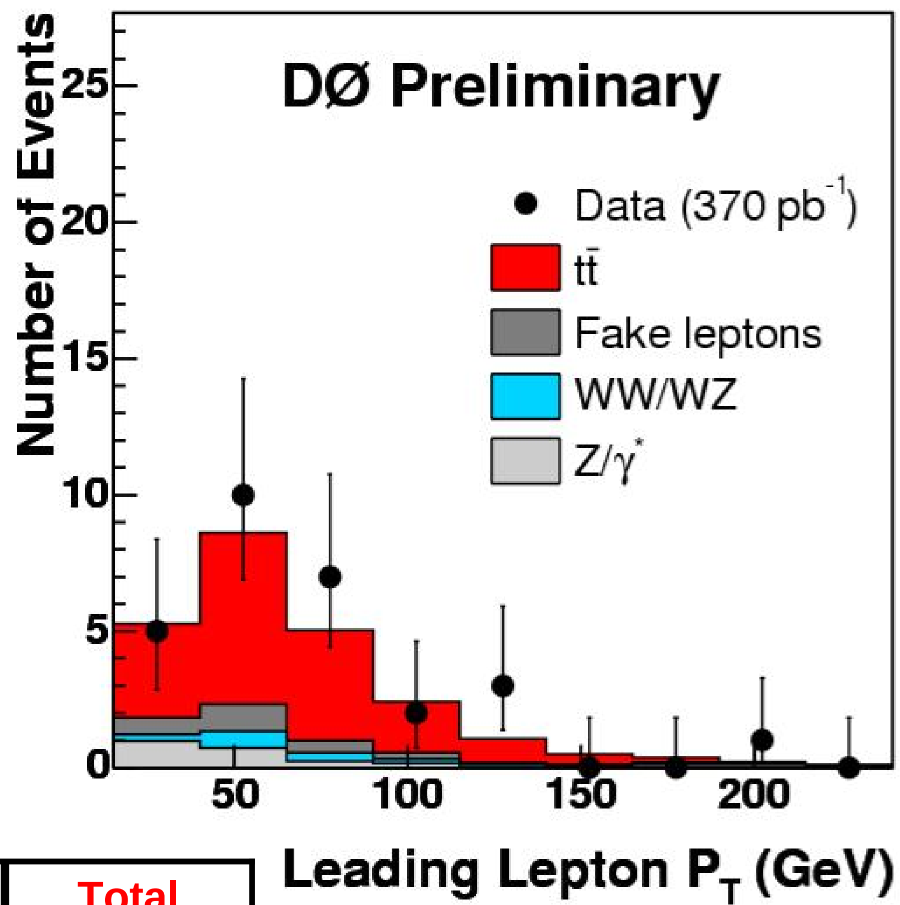


Z boson p_T (GeV/c)

Dilepton Final State

$\varepsilon \times BR(t\bar{t} \to dilepton) \approx 0.7\%$

- **Basic event selection**
  - **2 isolated electrons/muons E_T>15 GeV**
  - **At least 2 jets E_T>20 GeV**
- **Reduce main backgrounds:**
  - $Z/\gamma^* \to ee$ **with MET and sphericity**
  - $Z/\gamma^* \to \mu\mu$ **with MET and χ^2 consistency with Z mass**
  - $Z/\gamma^* \to \tau\tau$ **with Σp_T of jets and leading lepton**



Events	ee	μμ	eμ	Total
Bkg	1.0±0.3	1.3±0.4	4.5±2.2	6.8±2.2
Data	5	2	21	28

Fake leptons

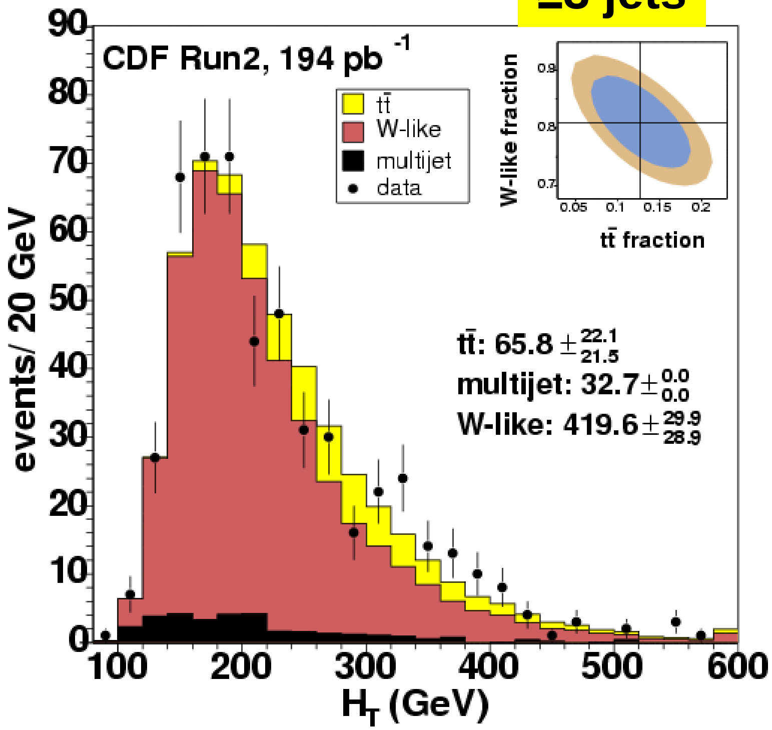
- Electron background from photon conversions
  - Especially at lower p_T
  - Reject by looking for two oppositely charged particle tracks that appear to be parallel from a common origin displaced from primary interaction point
  - Useful to “X-ray” detector and improve simulation modelling of material
- Muon background from decays in flight
  - Especially at higher p_T
  - Tracking reconstructs two separate tracks as one high p_T track
  - Reject by track chi2
- Fakes from jet fluctuations are difficult to estimate
  - Parameterize rate from jet data samples
  - If uncertainty too large for your analysis, recommend you spend your time improving lepton id rather than fake rate estimate

Lepton+Jets Final State

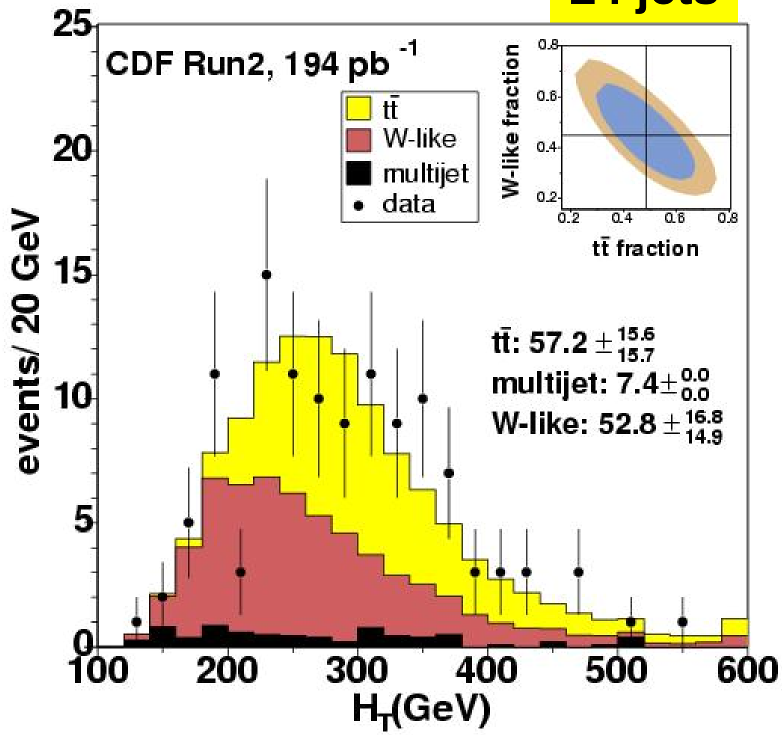
$\varepsilon \times BR(t\bar{t} \rightarrow lepton + jets) \approx 7\%$

- **Basic event selection**
  - **Isolated electron/muon E_T>20 GeV**
  - **At least 3 or 4 jets E_T>15 GeV with small cone of 0.4/0.5**
  - **MET>20 GeV**
- **Single variable gives some discrimination between top pair and W+jets**
- **Is S:B at LHC after event selection cuts similar or better?**

≥3 jets

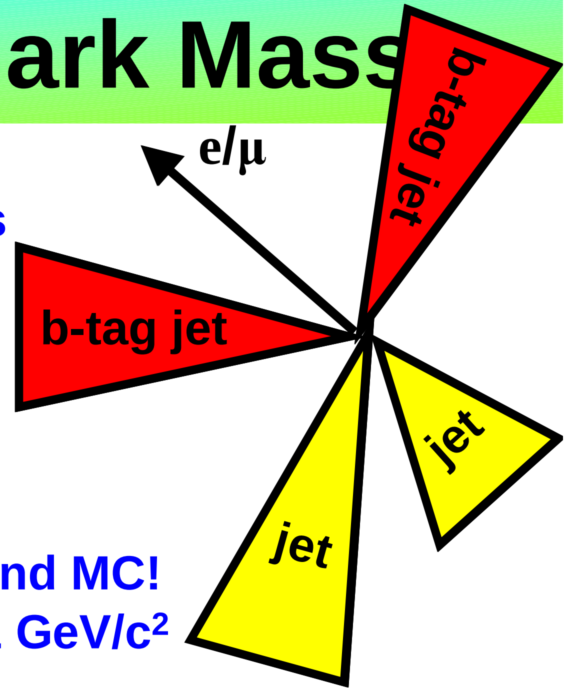


≥4 jets

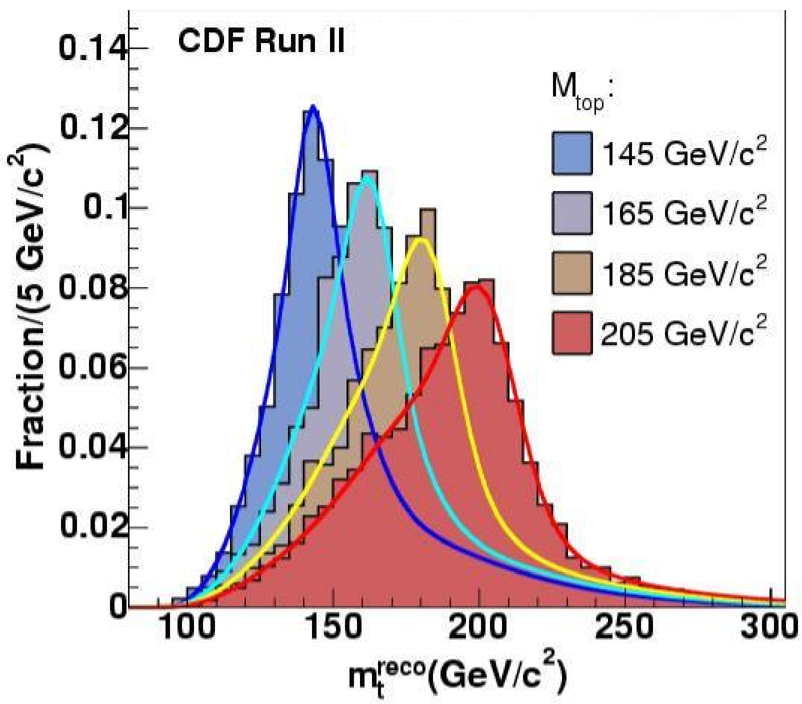


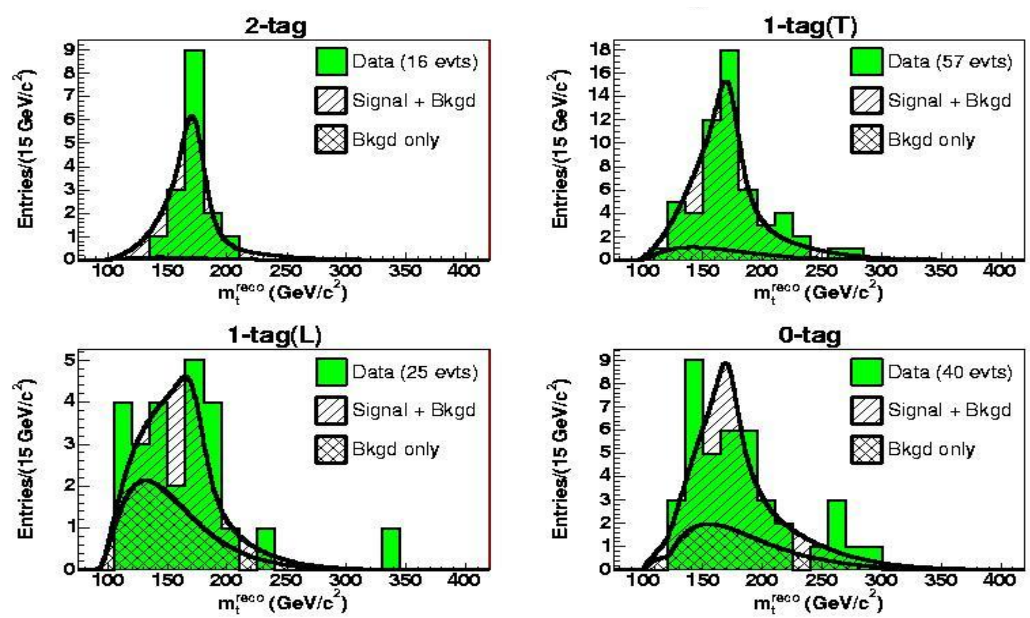
Combinatorics in Top Quark Mass

Kinematic fit to top pair production and decay hypothesis
- Obtain improved resolution on reconstructed top mass
- Choose most consistent solution for t→jjb and t→ℓυb
  - 24 possibilities for 0 b-tags
  - 12 possibilities for 1 b-tag
  - 4 possibilities for 2 b-tags

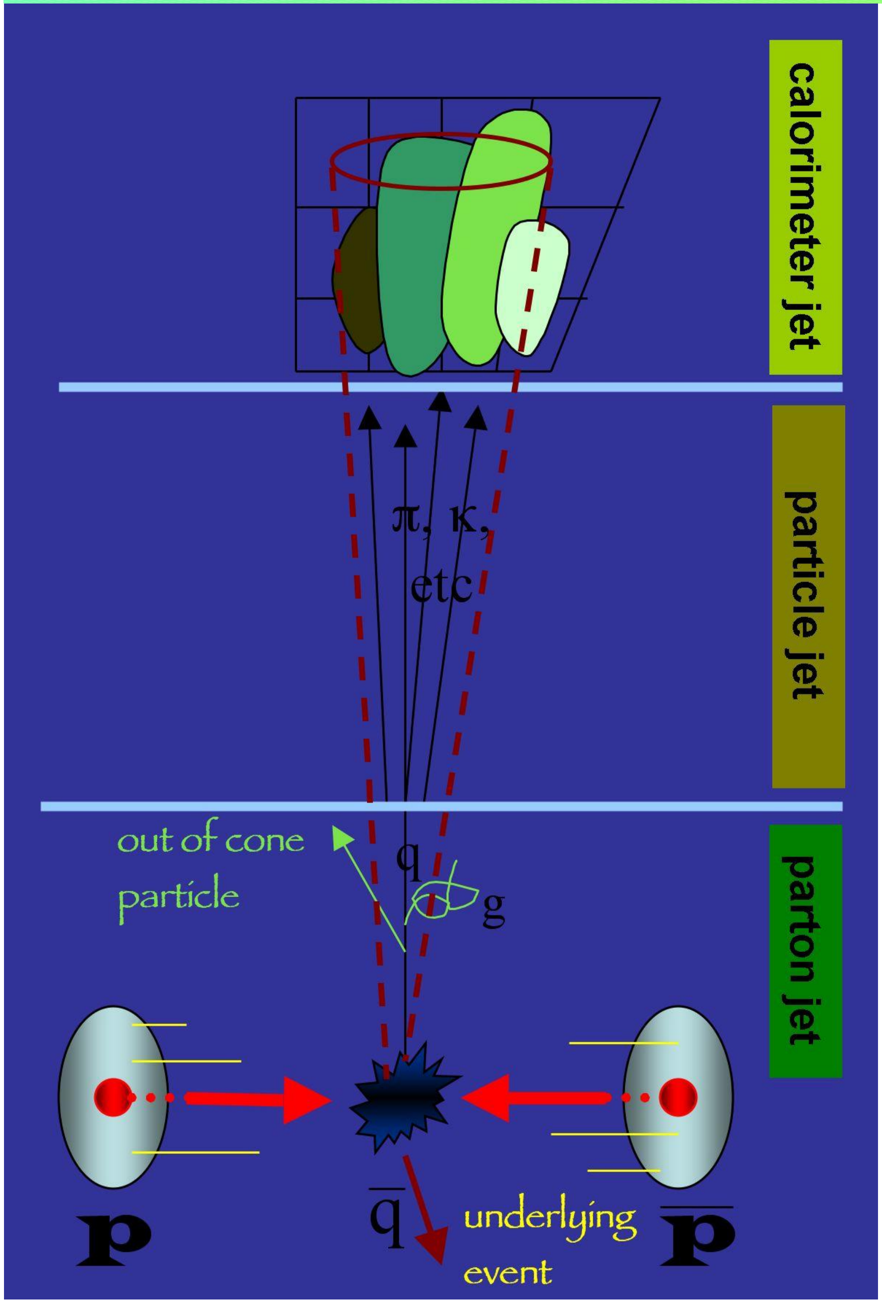


Fit data to reconstructed top mass distributions from MC
- Need excellent calibration of jet energy between data and MC!
- 1% systematic uncertainty on jet energy scale gives ~1 GeV/c^2 systematic uncertainty on top quark mass

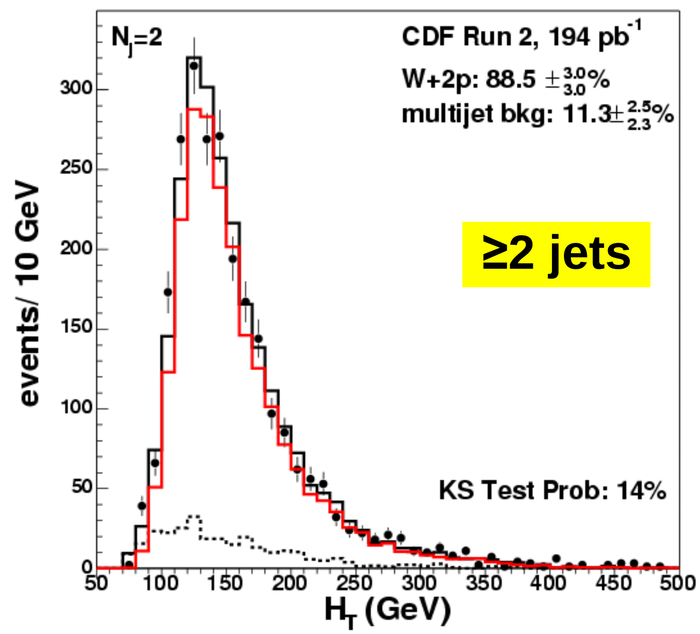




Systematic Uncertainty: Jet Energy Scale



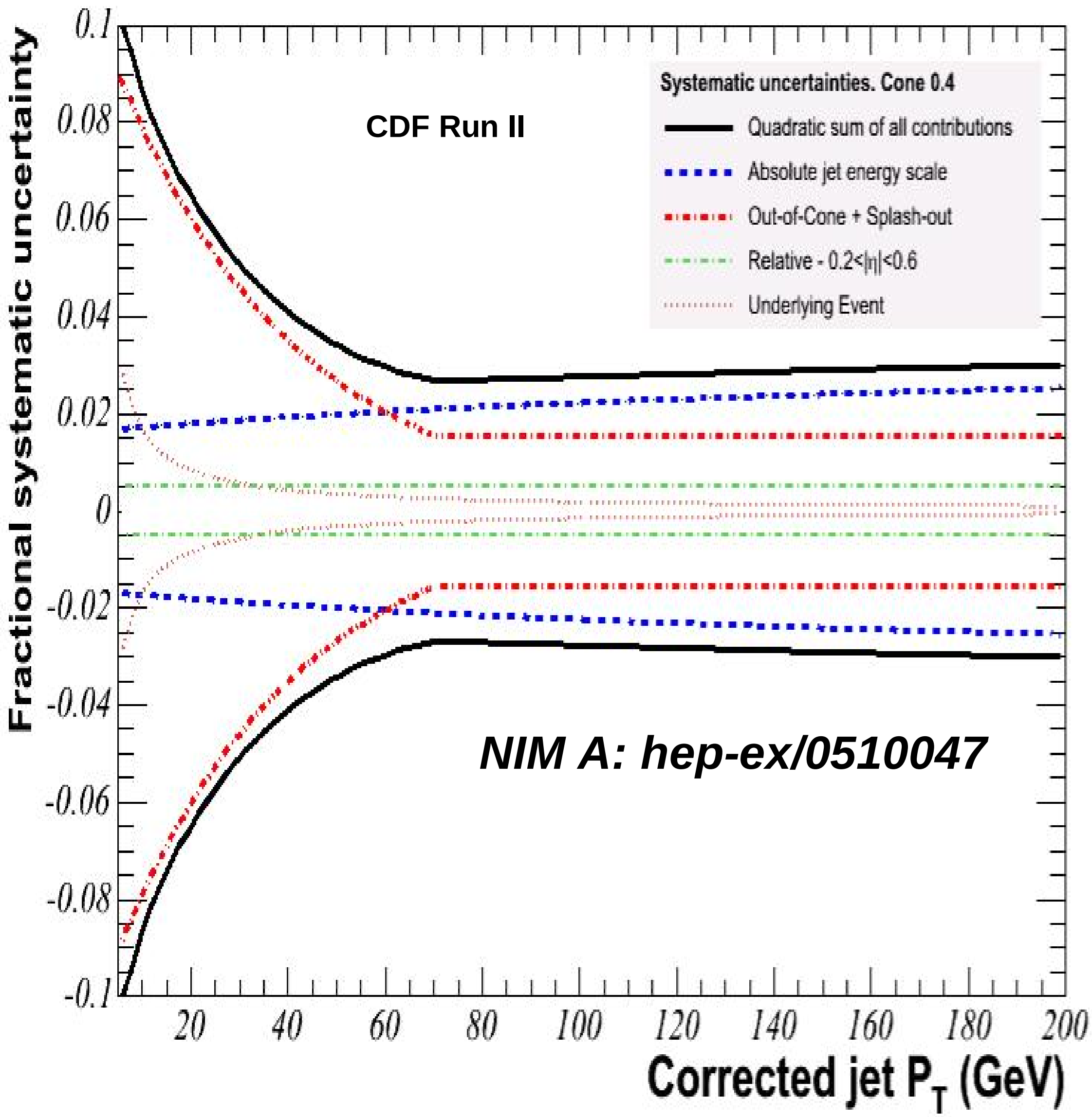
- **Caveat for kinematic observables related to jet energy**
  - **Important to calibrate jet energy scale otherwise data and MC distributions do not agree**
  - **Agreement was awful before detailed calibration**
  - **Top quark mass systematic was over 6 GeV/c^2**
  - **Took over a year to fix**



Jet Energy Scale

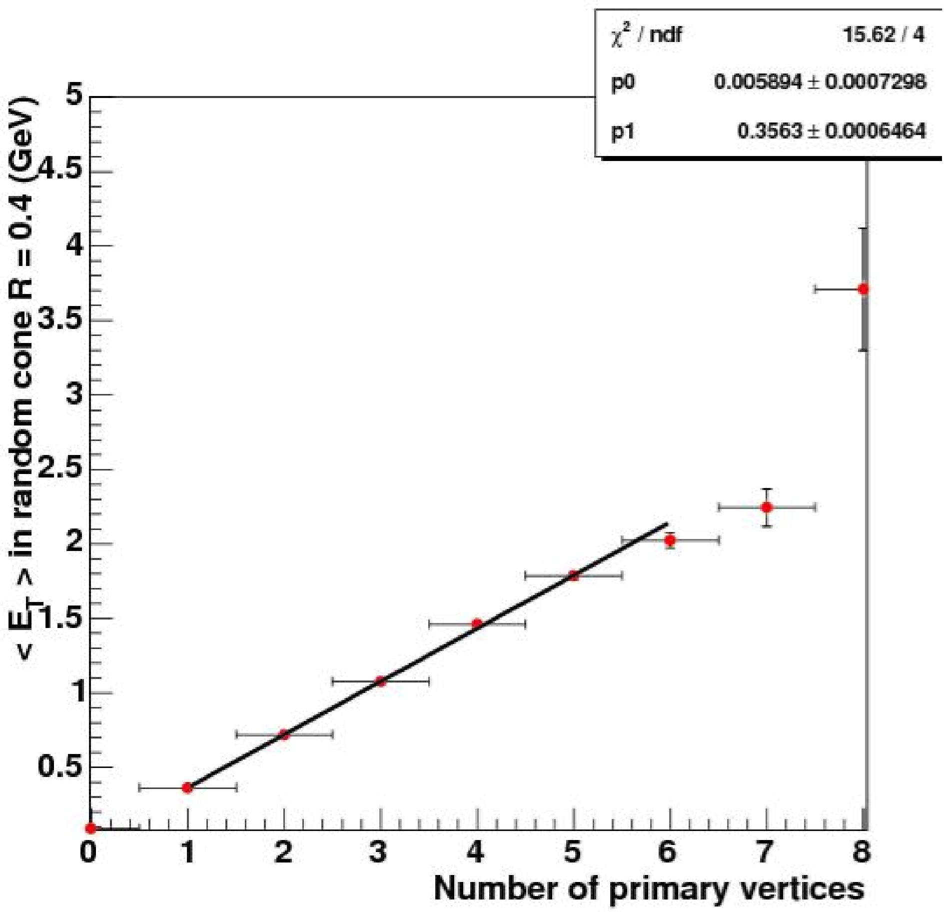
- At high p_T: dominant systematic from simulation modelling of calorimeter response
  - E/p for single isolated tracks essential to tune calorimeter simulation
- At low p_T: dominant systematic from modelling of amount of energy outside jet cone
  - Use narrow jet cones since top events have many jets
- Cross-check with better measured objects:
  - photon+jet
  - Z+jet

See Kenichi Hatakeyama's talk



Jet Energy Scale: Multiple pp Interactions

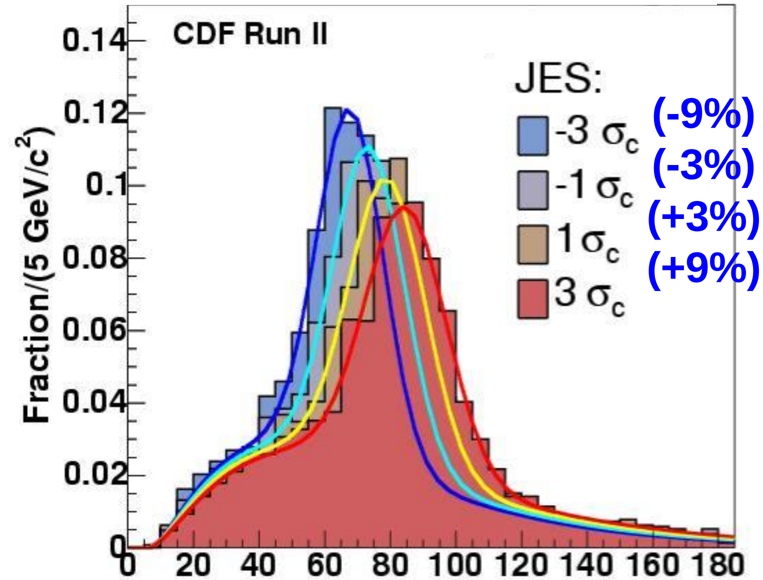
- More than one pair of pp (ppbar) interacts per bunch crossing?
  - Additional particles leave extra energy in detector
  - Jet clustering includes this extra energy
- Remove bias on an event-by-event basis
  - Determine number of distinct primary interaction vertices along beam-axis in an event
  - Apply correction derived from extra energy inside random jet cone in minimum bias data

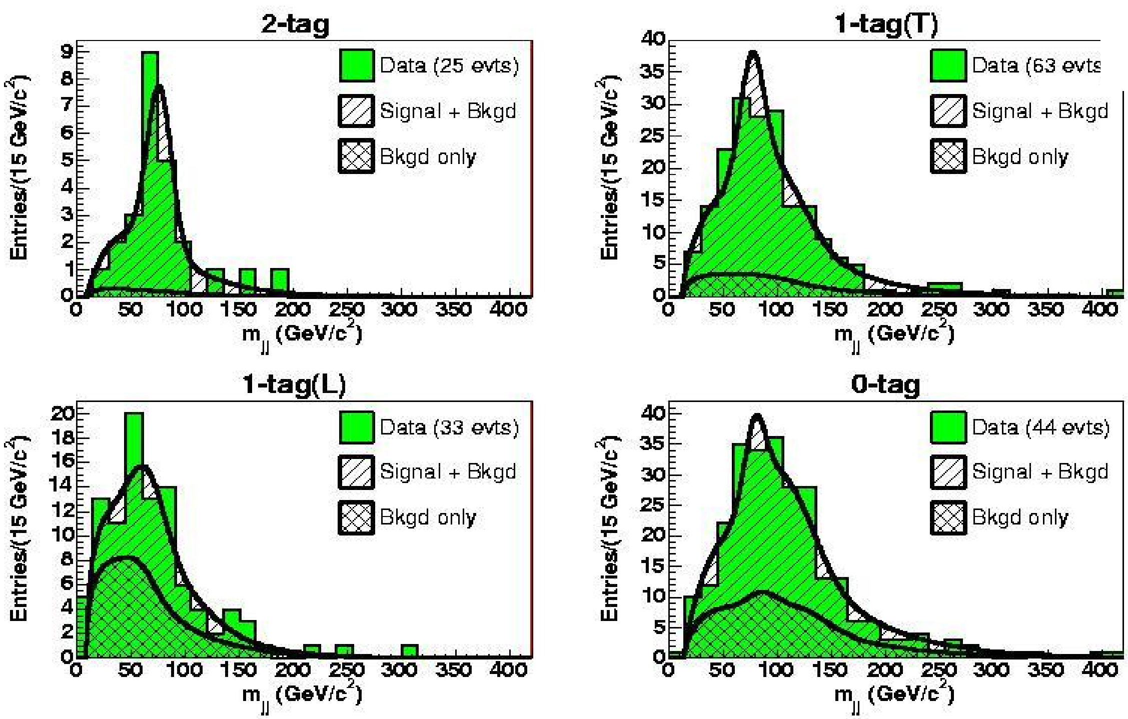


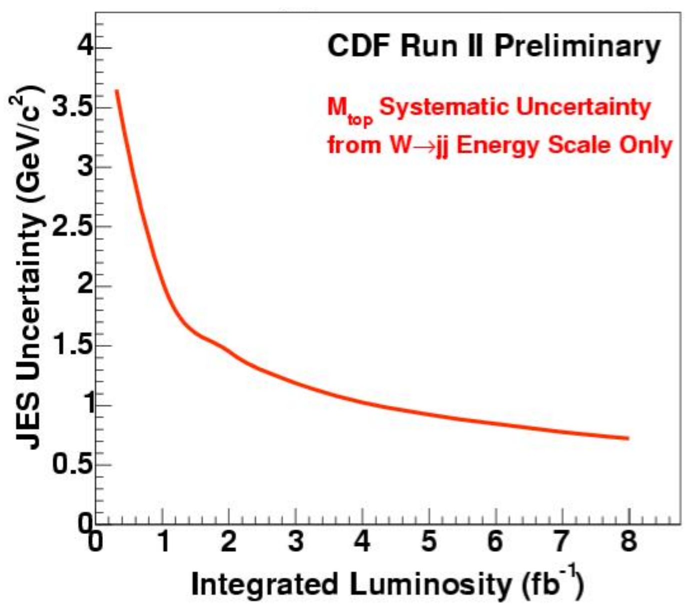
Answer to question:
RMS width of proton bunch about 30cm at Tevatron
Z-vertex resolution better than 0.5cm

Jet Energy Scale: W→jj *in situ* calibration

- Top lepton+jets final state provides only clean sample of W→jj at a hadron collider
  - W mass well-known from LEP & Tevatron
  - Reconstruct di-jet invariant mass
  - Use as extra constraint on jet energy scale
- Currently limited by data W→jj statistics
  - Note the method relies on good MC modelling of di-jet mass distribution, so still need excellent calorimeter simulation





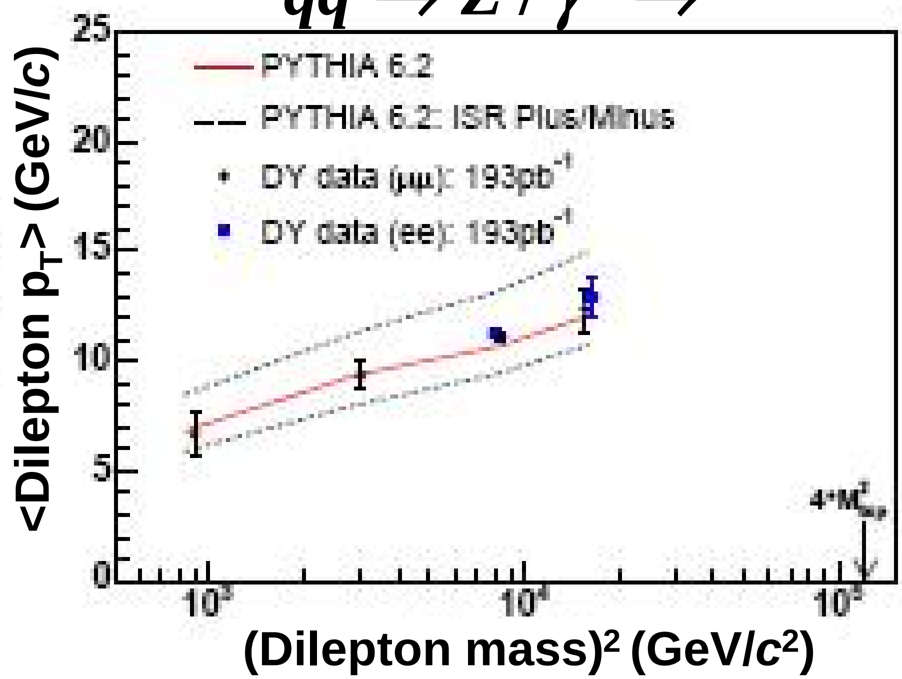


QCD radiation, b-jet energy scale

- QCD radiation can make additional jets from initial (ISR) and final (FSR) states
  - Drell-Yan has same initial state as 85% of top pair production
  - Dilepton p_T sensitive to ISR
  - Dilepton mass sets scale
  - FSR controlled by same parameters
- b-jet energy calibration
  - Estimate differences relative to light jet from MC/data studies
    - Fragmentation
    - Colour flow
    - Semi-leptonic decays
  - Calibrate directly from data
    - Z+b-jet balancing
    - Collect enough $Z \to b\bar{b}$ events

See Kenichi Hatakeyama's talk

$$q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$$

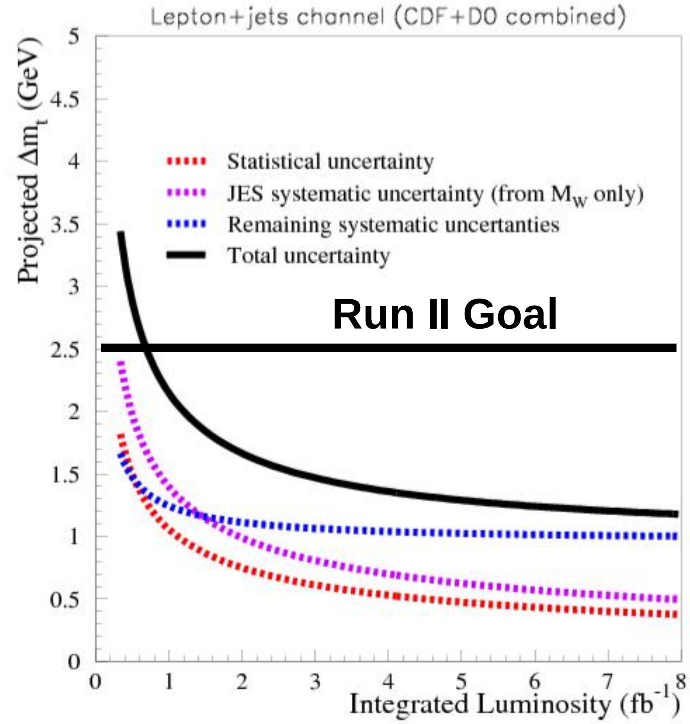


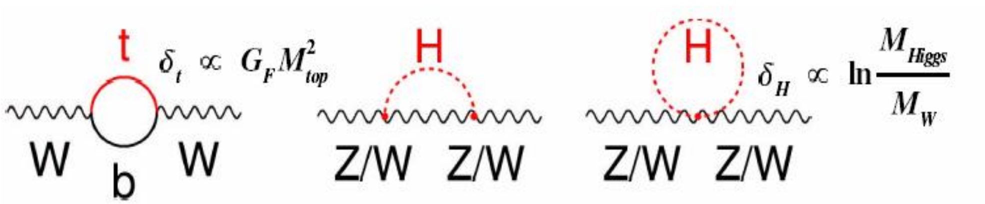
Systematic Source	CDF Top Mass Uncertainty (GeV/c²)
ISR/FSR	0.7
Model	0.7
b-jet	0.6
Method	0.6
PDF	0.3
Total	1.3
Jet Energy	2.5

Bright Future with Inverse Femtobarns!

CDF+D0 will achieve ±2.5 GeV/c² in 2006!
Will reach ±1.5 GeV/c with 4 fb⁻¹ base!

- **Shown is only lepton+jets channel with W→jj jet energy calibration**
- **Conservative estimate of other systematics, will get smarter with more data!**





Quantum loops make W mass sensitive to top and Higgs mass

- **Recent theoretical calculation of full two-loop electroweak corrections**
- **Precise prediction of W mass in standard model limited by uncertainty on experimental measurement of top mass**

Adapted from A. Freitas *et al* hep/ph-0311148	Experiment δM_{top} (GeV/c²)	Prediction δM_W (MeV/c²)
CDF+D0 Run I	4.3	26
CDF+D0 2005	2.9	18
CDF+D0 1 fb⁻¹	2.0	12
CDF+D0 4 fb⁻¹	1.5	9
LHC	1.3	8

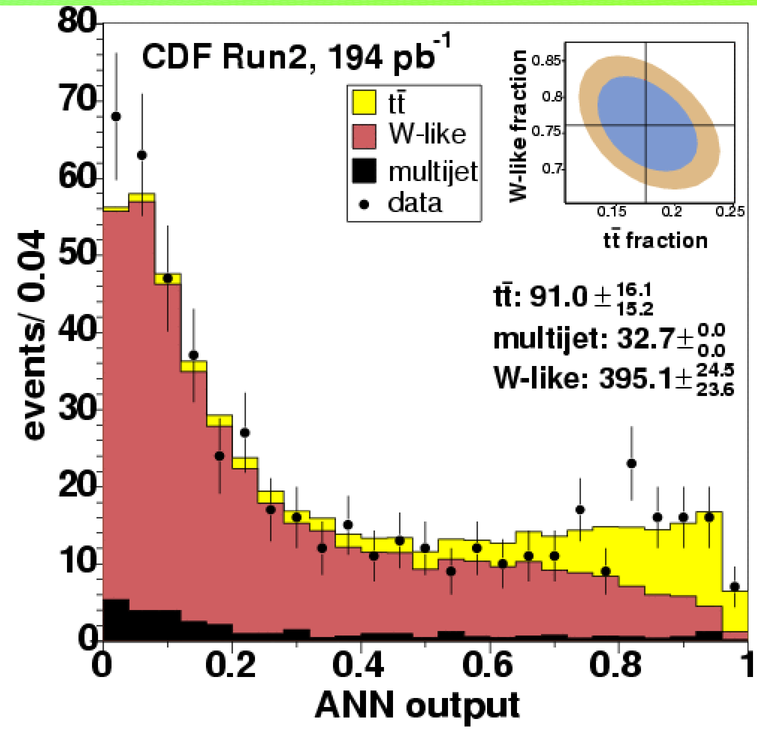
Advanced multivariate techniques

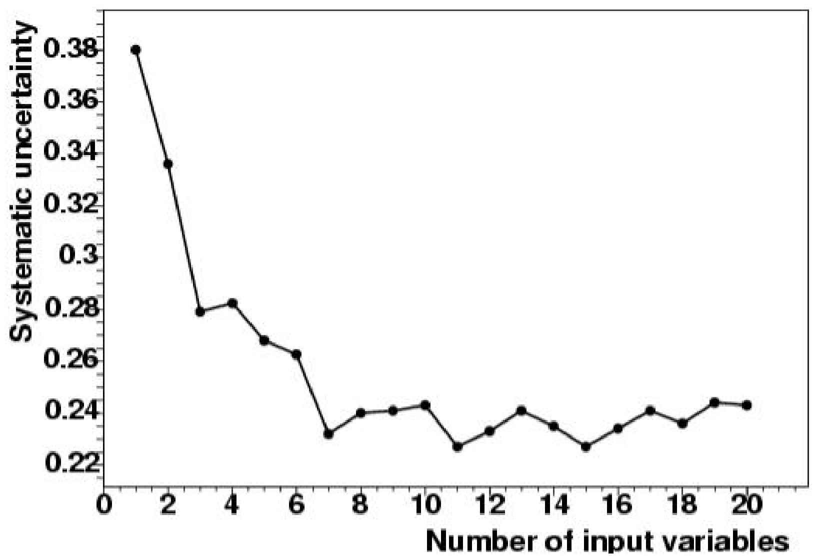
- **Having proven good modeling of background and jets…**
- **…can improve discrimination by combining several kinematic event observables**
  - **Artificial neural network**
  - **Decision tree**
  - **Genetic algorithm**

See Yann Coadou's talk

- **Optimize to reduce both statistical and systematic uncertainty**
  - **Trade systematically challenged jet energy observables for angular observables**

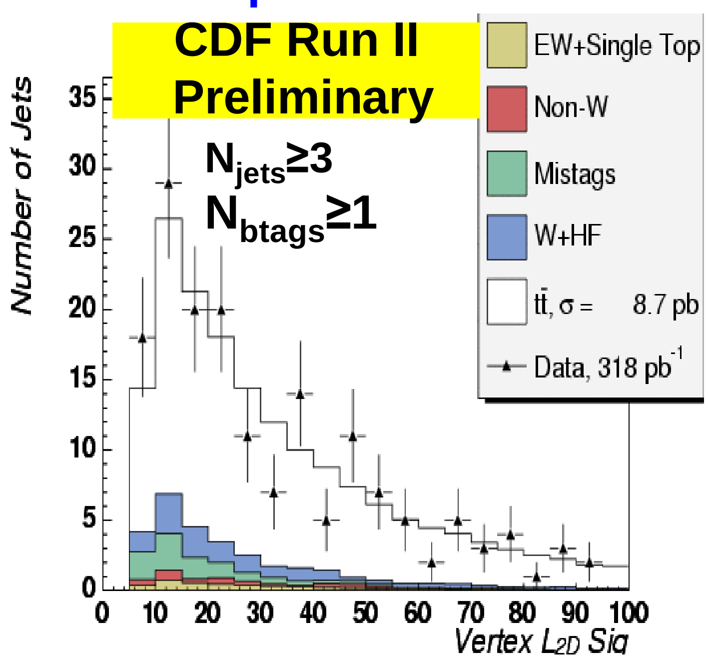
- **Always ask yourself: is all this sophistication making any difference? Compare to single best event observable**

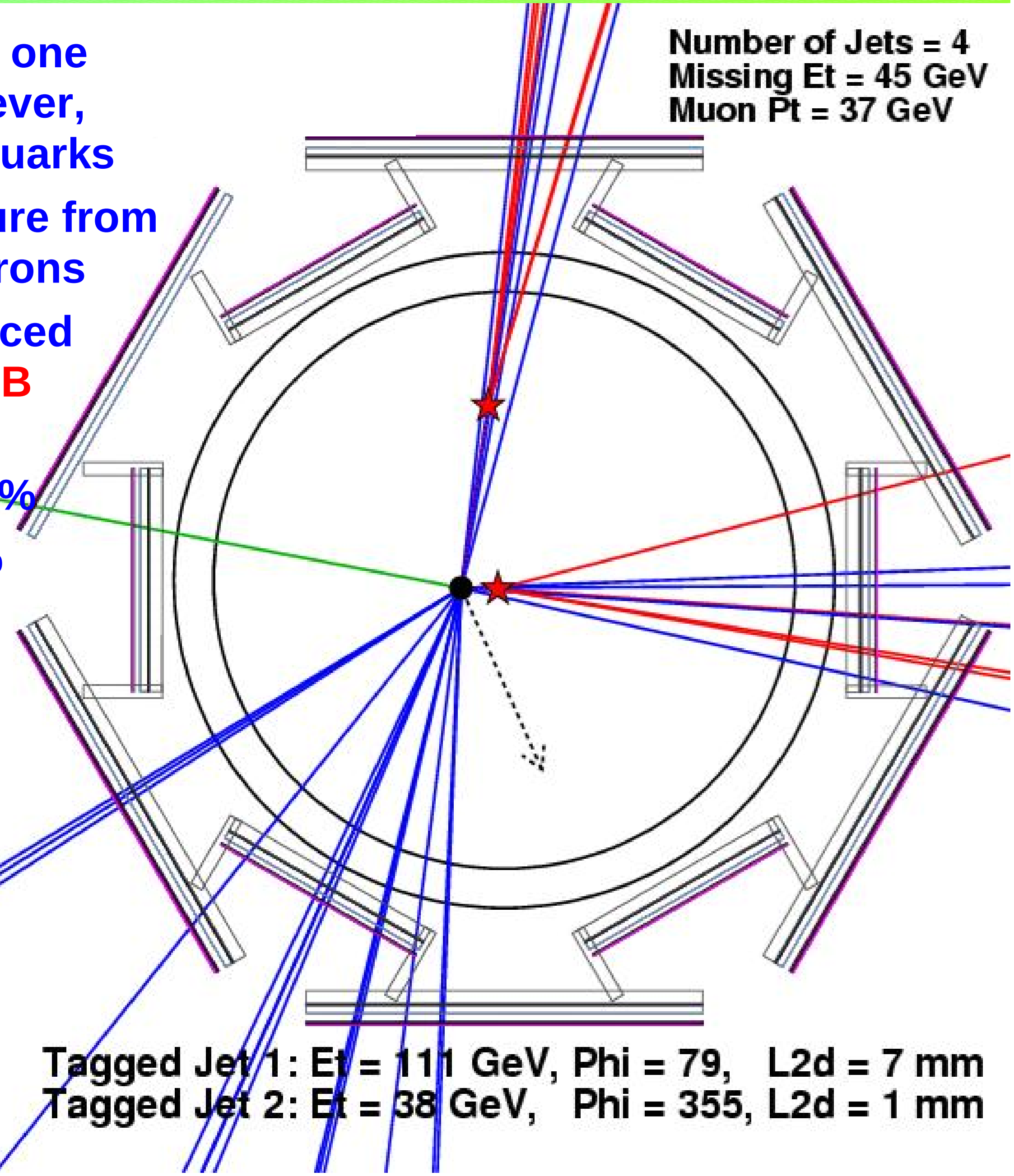




b-tagging

- Each top quark decay produces one energetic central b-quark, however, only few % W+jets have b or c quarks
- Distinctive experimental signature from long lifetimes of massive B hadrons
- Reconstruct significantly displaced secondary vertex from charged B decay products inside jet
  - Efficiency per b-jet about 50%
  - False positive rate about 1%

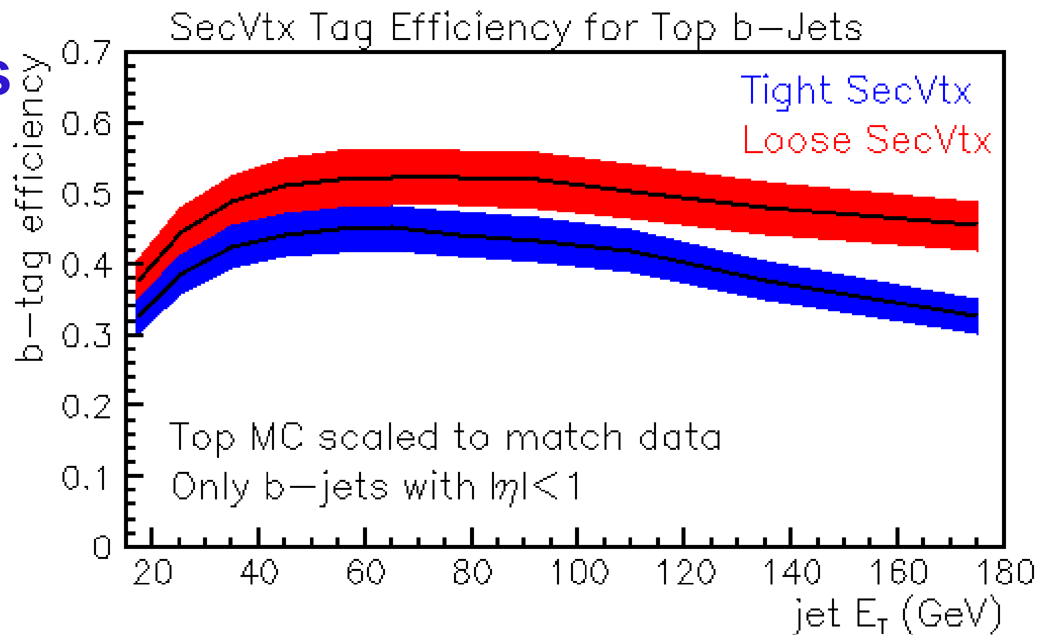


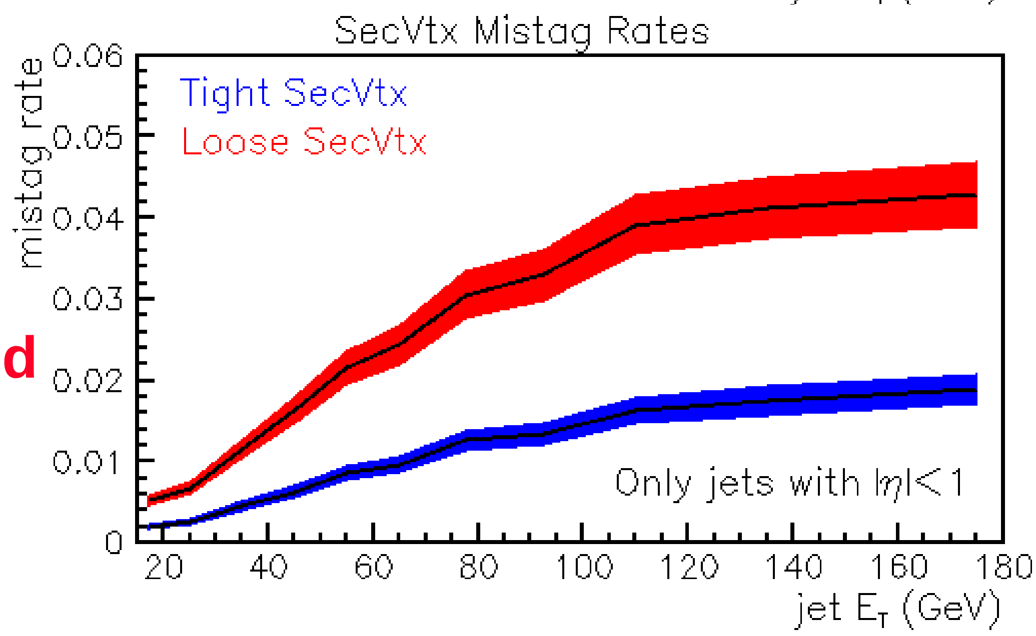


b-tagging: Calibration

- No good control samples of b-jets at high E_T
  - Di-jet data
  - Extrapolate check to signal jet E_T region
  - LHC: use top pair production?
- MC does not model tails in experimental distributions well
  - Parameterize from jet data as a function of jet E_T,η,φ,number of charged tracks, etcetera

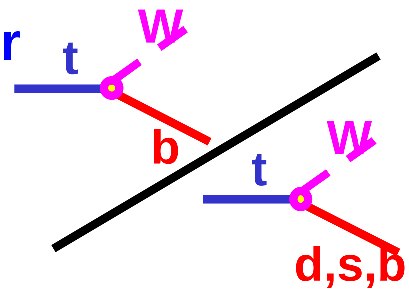
See Christopher Neu's talk

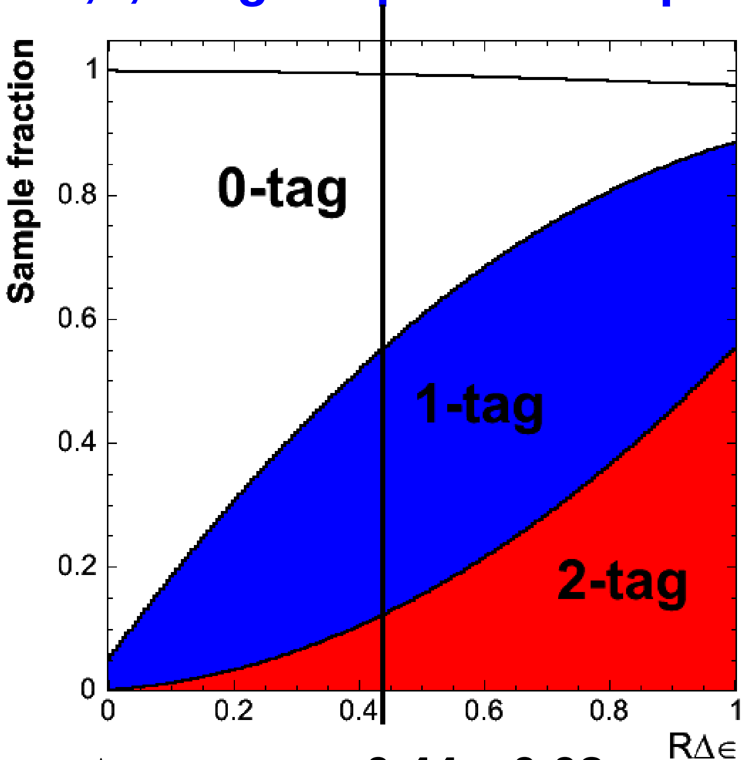




b-tagging: Calibration from top pairs?

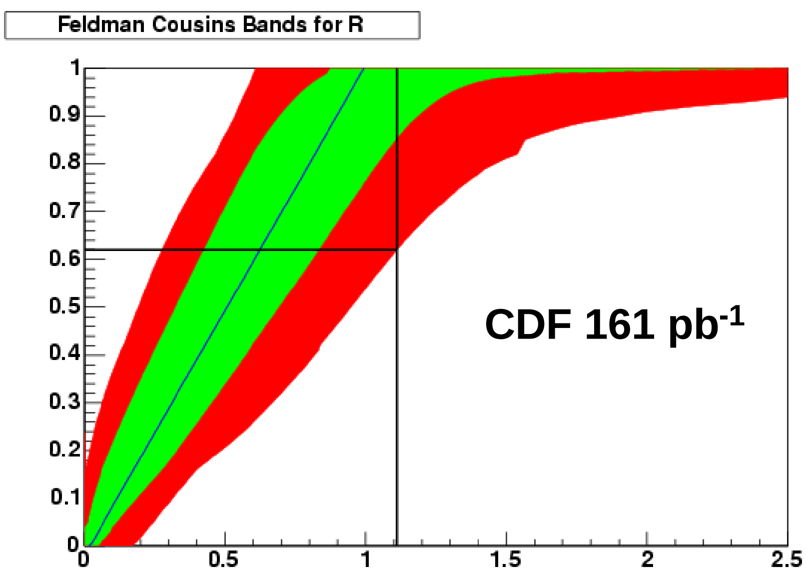
- If BR(t→Wb) is lower than SM prediction of ~100%, or if b-tag efficiency is lower than estimated value
  - observe fewer double b-tag events
  - observe more events without any b-tags
- Fit R=BR(t→Wb) / BR(t→Wq) times b-tag efficiency from observed number and estimated composition of 0,1,2-tag dilepton and lepton+jets events





$\Delta\varepsilon = \varepsilon_b - \varepsilon_{light} = 0.44 \pm 0.03$
from independent estimate

Best fit $R = 1.11^{+0.21}_{-0.26}$



R>0.62 @ 95% C.L.

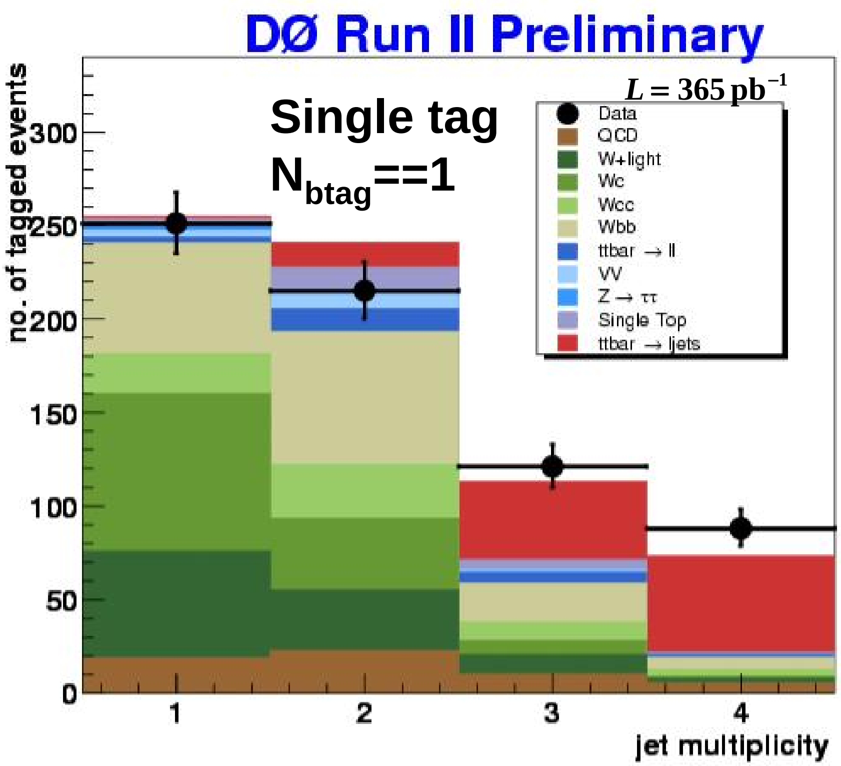
Lepton+Jets with b-tagging

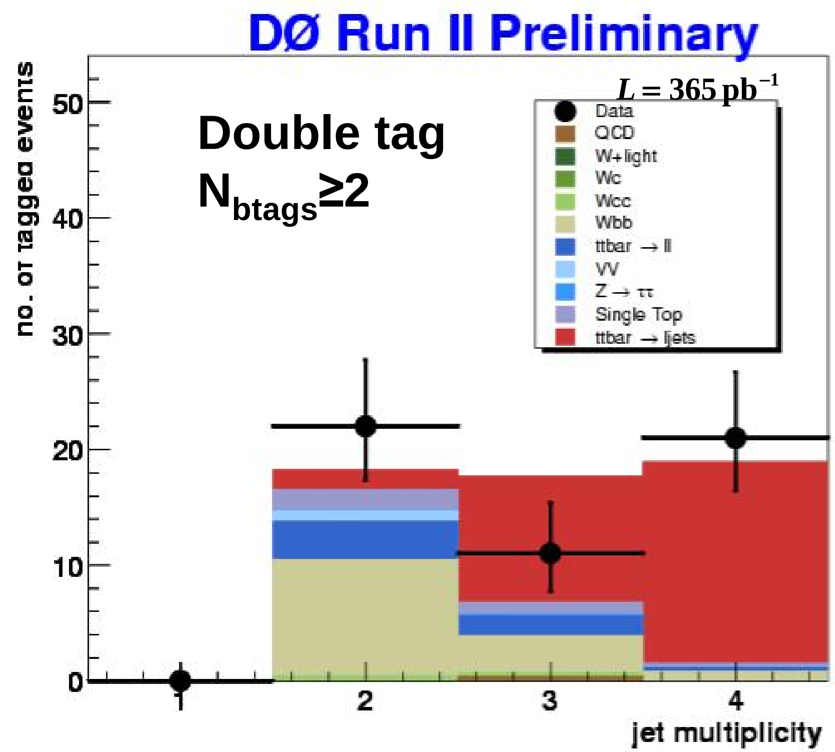
$\varepsilon \times BR(t\bar{t} \rightarrow {}^{a} + jets) \approx 4\%$

$\sigma(t\bar{t}) = 8.1 \pm 0.9(\mathrm{stat}) \pm^{0.9}_{0.8} (\mathrm{syst}) \pm 0.5(\mathrm{lumi})\,\mathrm{pb}$

Events	Control region		Signal region	
N_{btag}=1	W+1 jet	W+2 jets	W+3 jets	W+≥4 jets
Bkg	254±38	228±31	71±9	22±2
Data	251	215	121	88

Events	Control	Signal region	
N_{btags}≥2	W+2 jets	W+3 jets	W+≥4 jets
Bkg	17±3	7±1	1.9±0.3
Data	22	11	21





Estimate of W+HF production with LO MC

- LO MC prediction for W+HF rate uncertain by 50%
- Assume MC fraction of W+HF is better modelled
  - Systematic effects cancel in ratio
- Derive data-normalized estimate of W+HF as

$$N_{data}^{W+jets} \times \frac{N_{MC}^{W+HF}}{N_{MC}^{W+jets}} \times \varepsilon(\mathrm{b-tag})_{MC}^{W+HF}$$

Data number of W+jets events before b-tag
Correct for non-W processes, including ttbar

MC fraction of W+jets from HF

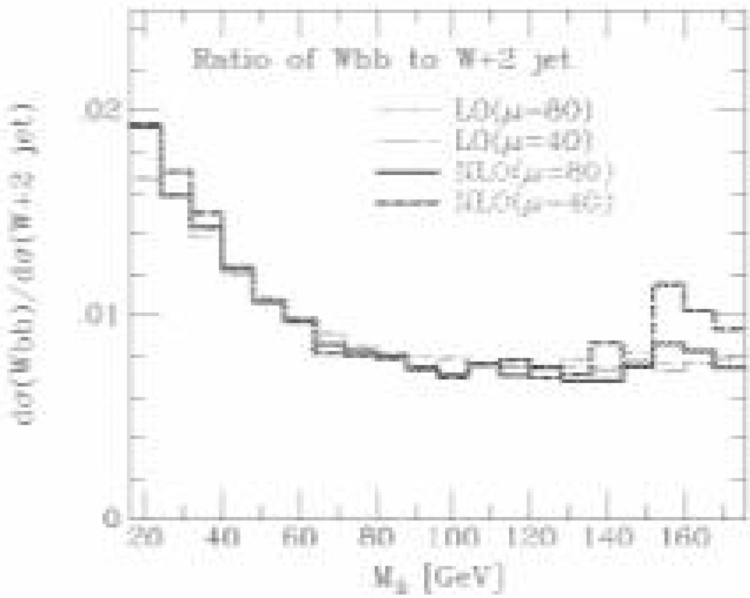
b-tag efficiency for W+HF MC
Scale by data/MC b-tag ratio

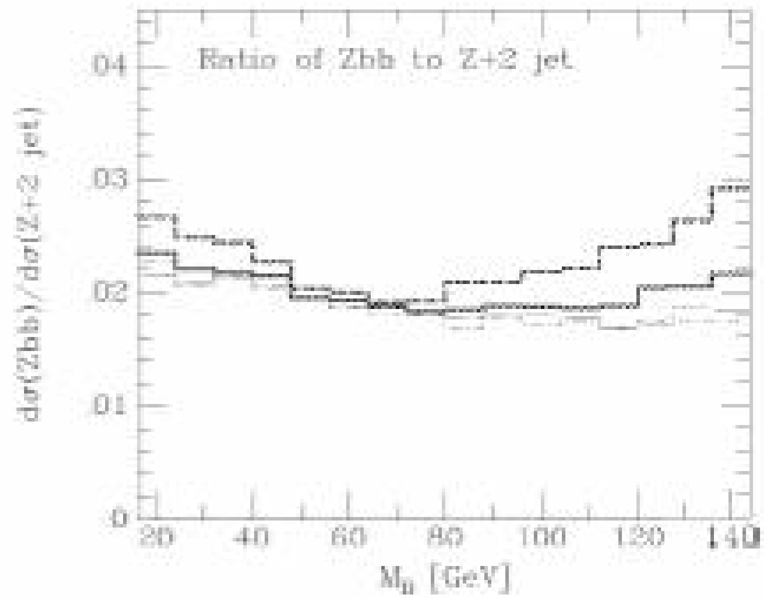
20-30% systematic from matching of LO matrix element to parton shower
May decrease with new version of ALPGEN

W+HF fraction

- **Tevatron: MCFM study of W/Z+HF fraction**
  - **Stable between LO and NLO**
  - **Almost independent of scale**
- **D0 and CDF performing measurements of W/Z+HF**
  - **D0 Zb/Zj PRL94 161801 (2005)**
  - **D0 Wbb PRL94 091802 (2005)**

MCFM (Tevatron) hep-ph/0202176 (LHC) hep-ph/0308195

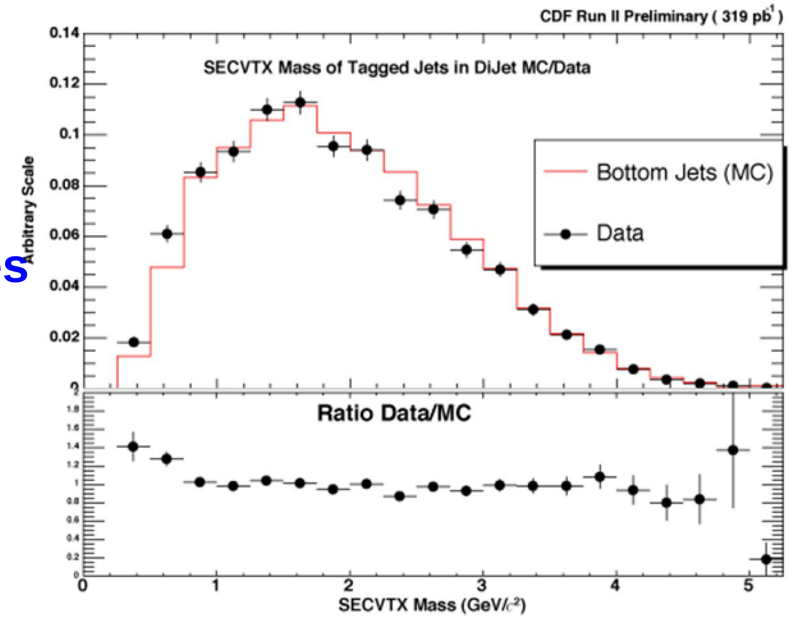


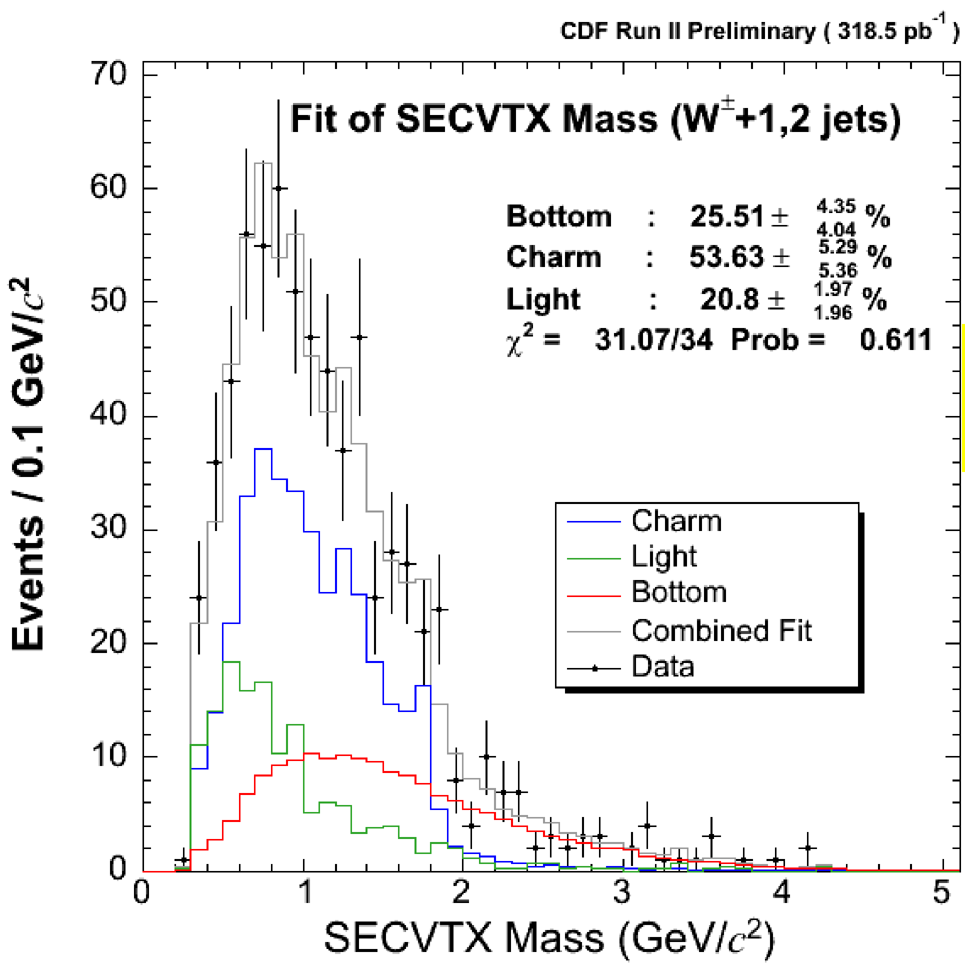


Checking Wbb production rate

Invariant Mass of all charged particle tracks from significantly displaced secondary vertex

- Discriminate between b/c/light flavor
- Check b MC model in double-tag di-jet events
- Several light flavor models have similar shapes





$$\frac{Wb\bar{b}}{W+1,2\,jets} = 0.72 \pm 0.24(\text{stat}) \pm 0.22(\text{syst})\%$$

Difficult to check charm MC model, and measurement complicated by large amount of charm from Wcc and Wc in this "b"-tagged sample!

- Developing tools to reject secondary vertices from charm quark decays
- Applicable to flagship searches for single top and WH as well

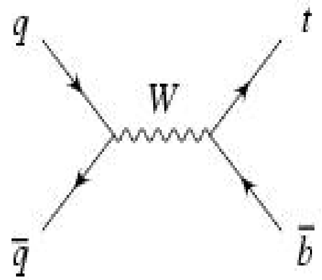
Does something new produce Single Top Quarks?

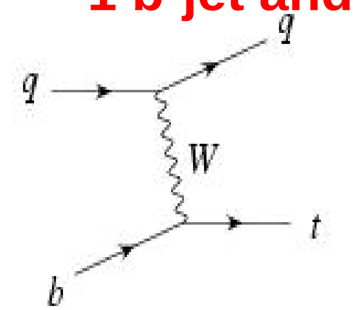
Single top quark production via electroweak interaction
Cross section proportional to $|V_{tb}|^2$

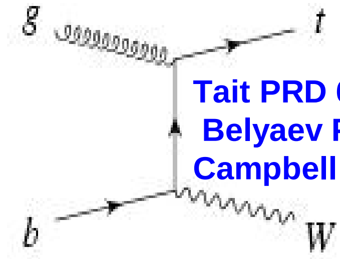
Trigger on lepton from $t \to Wb \to \ell \upsilon b$

2 b-jets for s-channel **1 b-jet and 1 light jet for t-channel**

Harris PRD 66 (02) 054024
Cao hep-ph/0409040
Campbell PRD 70 (04) 094012







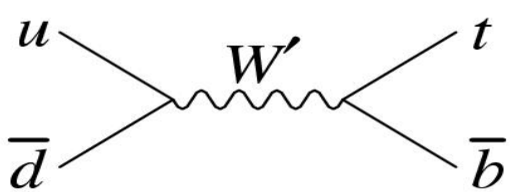
Tait PRD 61 (00) 034001
Belyaev PRD 63 (01) 034012
Campbell hep-ph/0506289

$\sqrt{s}$=1.96 TeV:	0.88 ± 0.11 pb	1.98 ± 0.25 pb	<0.1 pb
$\sqrt{s}$=14 TeV:	10.6 ± 1.1 pb	246.6 ± 11.8 pb	62.0+16.6-3.6 pb

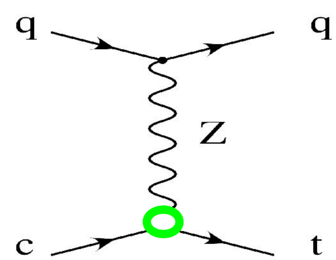
Interesting to measure different channels – sensitive to different physics

See Tait, Yuan
PRD63, 014018 (2001)

s-channel
Sensitive to new resonances



t-channel
Sensitive to FCNCs



D0 Search for Single Top Quark Production

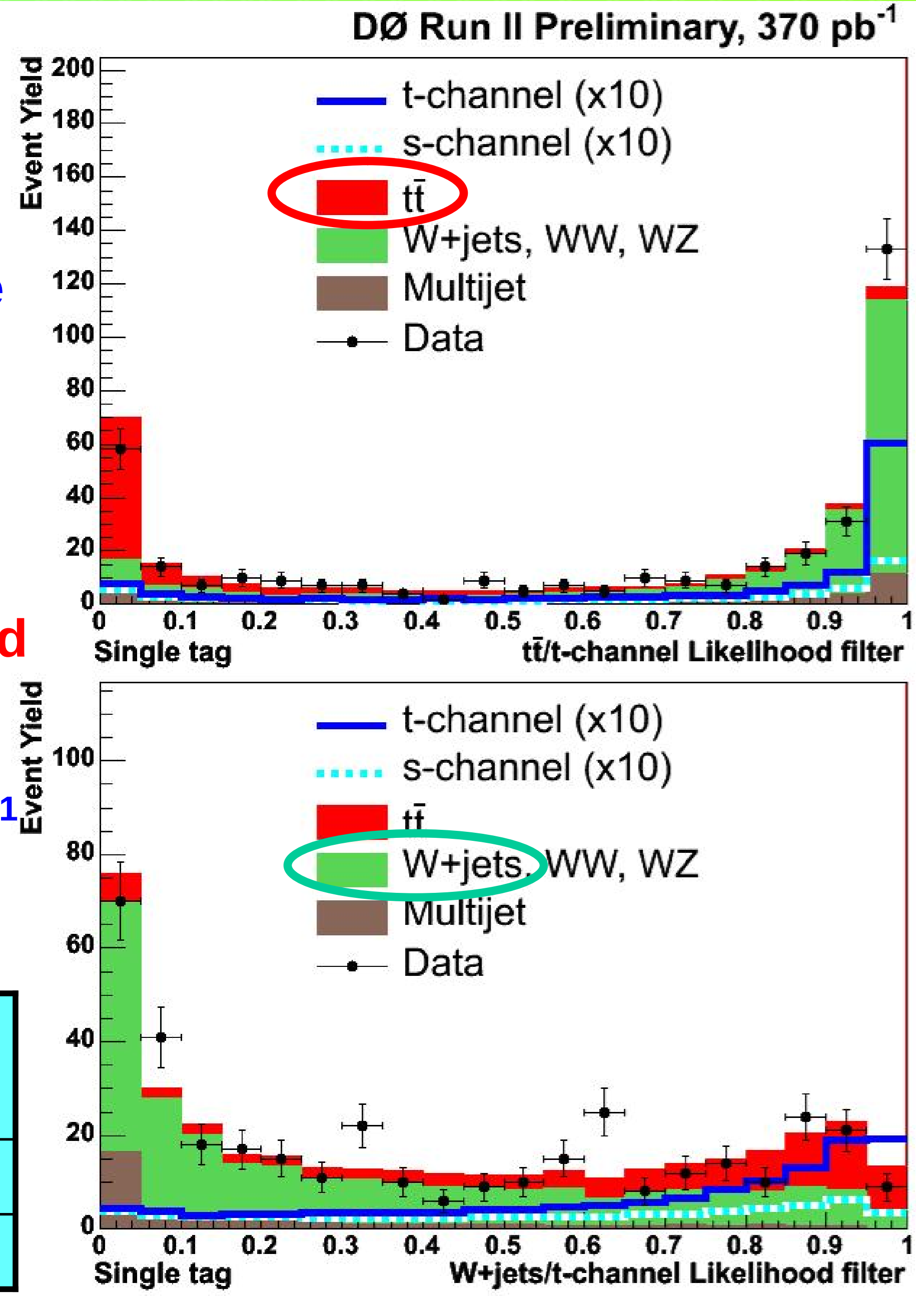
- Why is it difficult?
  - Signal swamped by W+jets
  - Signal sandwiched between W+jets and top pair production
- Dedicated likelihood to discriminate between each signal and each background

See Yann Coadou's talk

- Rely on good MC modeling of W+jets background composition and kinematics
  - Big challenge for discovery!
  - 3σ evidence expected with <2 fb^{-1}

D0 Preliminary: World's best limits!
Factor of 2-3 away from standard model

D0 370 pb^{-1}	Expected 95% C.L. (pb)	Observed 95% C.L. (pb)
s-channel	3.3	5.0
t-channel	4.3	4.4



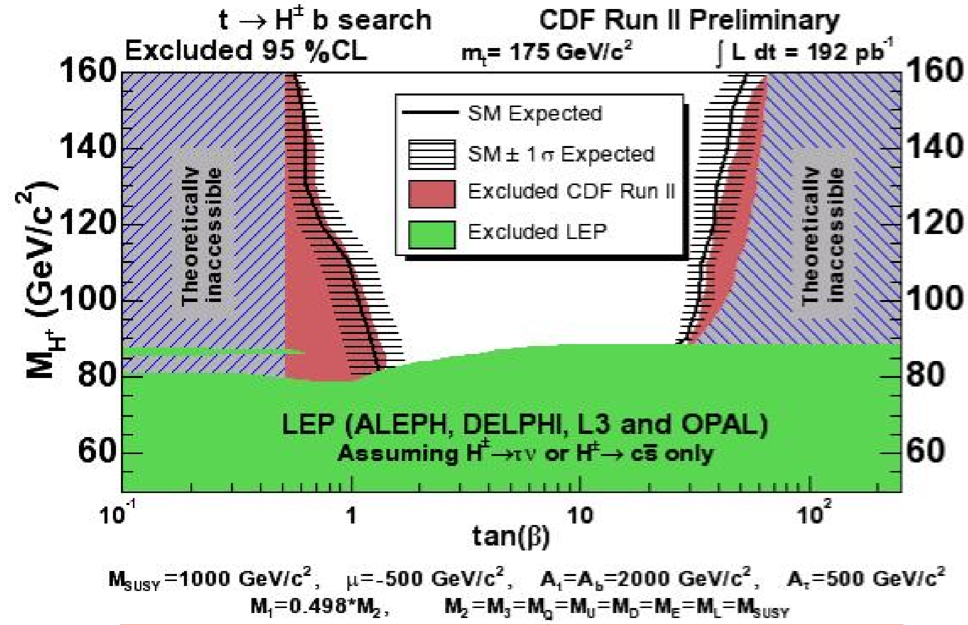
Subtle effects: Does top always decay to W^+b?

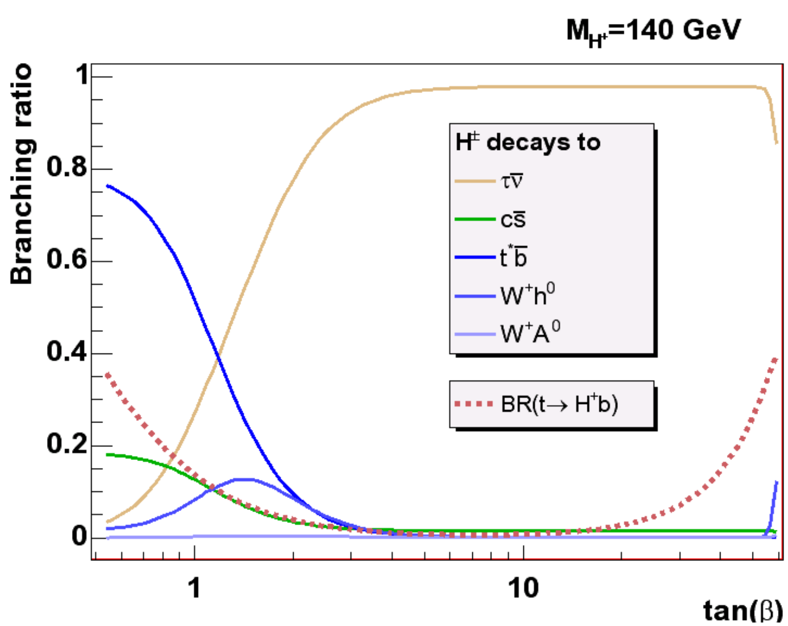
Branching ratio for $t \to H^+ b$ significant (>10%) for small and large $\tan\beta$

H^+ decays differently than W^+

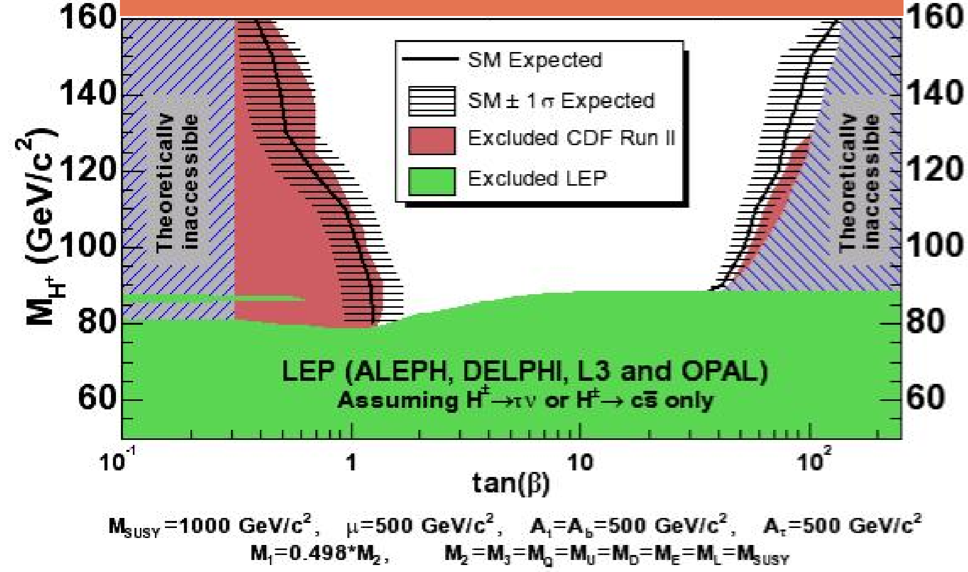
- $H^+ \to \tau^+ \upsilon_\tau$ enhanced if high $\tan\beta$: observe more taus!
- $H^+ \to t^* b \to W^+ bb$ for high $m(H^+)$ if low $\tan\beta$: mimics SM signature but observe more b-tags

Compare number of observed events in 4 final states: dilepton, $e\tau_h + \mu\tau_h$, lepton+jets with single b-tag, and lepton+jets with double b-tags





Set limits in several MSSM scenarios with NLO corrections



Statistical techniques

- What if you don’t know what the signal looks like? How do you isolate events unlikely to be from standard model?
  - Quantify agreement between data and standard model for kinematic distributions
  - Isolate subset of events with largest concentration of non-SM properties and quantify disagreement
- Example: Search for anomalous kinematics in top dilepton
  - Choose *a priori* kinematic distributions **PRL95 022001 (2005)**
    - Leading lepton p_T
    - MET
    - Angle between leading lepton and MET
    - Top-likeness of event
  - Compute SM probability to have value > or < observed
  - Order events into least-likely subsets and quantify with Kolmogorov-Smirnov tests

Top Techniques

- **Matrix element techniques for top mass, W helicity,…**
  - **Pros**
    - **Use maximum amount of information to extract maximum sensitivity**
    - **Sum over all possible combinations, so always include correct combination**
  - **Cons**
    - **Extremely CPU intensive: Integrations can take ~~seconds~~ hours! per event**
    - **Less optimal for events that do not satisfy simplifying assumptions**

- **Blind analysis techniques**
  - **No fit to data distribution until all checks are complete to satisfaction of entire group**
  - **Require blind test samples**
    - **Generate events and drop truth level information**
    - **Check mass analysis techniques really are unbiased**
  - **Honor system**
    - **Use same data for other measurements**
    - **Have to convince entire group not to show or look at certain distributions like ttbar mass or top mass**

Top Tools

- Common event selection
  - No despair over single event differences
  - Can easily combine results
  - Can compare measurements of different properties
- Common analysis ntuple for efficient use of CPU resources
  - Only done once for entire group
  - Quick: In parallel with many queues of group members
- Common MC samples for efficient use of CPU resources
  - Will be used as SM background by everyone else
  - Extensive validation is *de rigeur*
  - Quick: In parallel with many queues of group members
- Work as a team
  - Cross-checks essential to find bugs in complex code
  - New ideas can be explored for better results

Conclusions

Top Quark Physics
requires good understanding
of entire detector!

Early effort to understand Jet Energy Scale essential
for event kinematics and top quark mass

b-tagging invaluable to reduce
combinatorics for measurements of top quark properties
and irreducible backgrounds

Sophisticated techniques fun and can find
subtle effects or
least likely subset of events from standard model

Team work and efficient tools essential for success!

Matching in ALPGEN+HERWIG

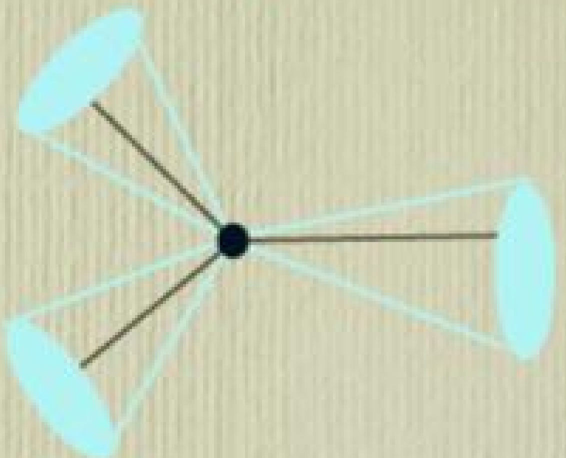
(From http://mlm.home.cern.ch/mlm/talks/lund-alpgen.pdf)

- **Generate parton-level configurations** for a given hard-parton multiplicity N_{part}, with partons constrained by
  - $p_T > p_{T\,min}$ $\Delta R_{jj} > R_{min}$
- **Perform the jet showering**, using the default Herwig/Pythia algorithms
- Process the showered event (**before hadronization**) with a **cone jet algorithm**, defined by $E_{T\,min}$ and R_{jet}
- **Match partons and jets:**
  - for each hard parton, select the jet with min $\Delta R_{j\text{-}parton}$
  - if $\Delta R_{j\text{-}parton} < R_{jet}$ the parton is "matched"
  - a jet can only be matched to a single parton
  - **if all partons are matched, keep the event, else discard it**
- This prescription defines an **inclusive sample** of $N_{jet}=N_{part}$ **jets**
- Define an **exclusive N-jet** sample by requiring that the number of reconstructed showered jets N_{jet} be equal to N_{part}
- After matching, combine the exclusive event samples to obtain an **inclusive sample containing events with all multiplicities**

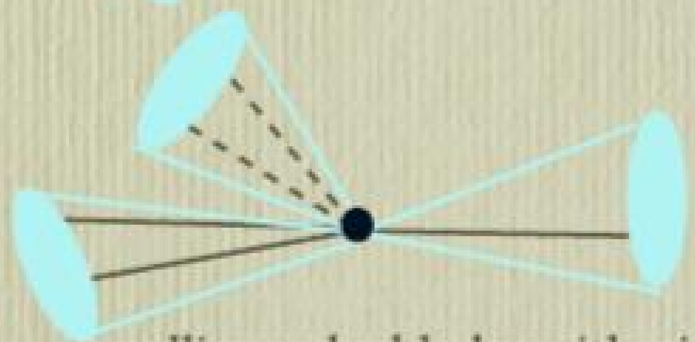
Few examples of matching:

hard parton

parton emitted by the shower



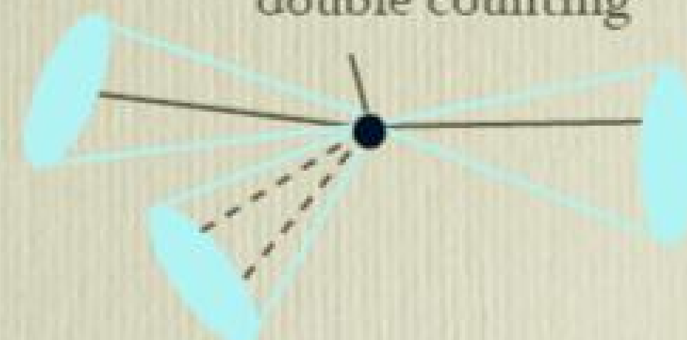
Event matched, $N_{jet}=N_{part}=3$, keep

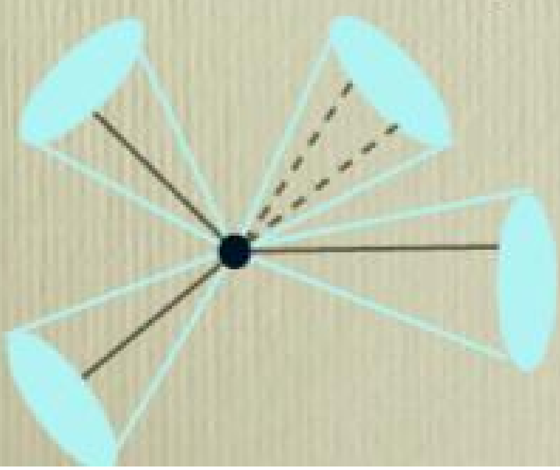


collinear double-logarithmic double counting

NOT matched, $N_{jet}=N_{part}=3$, but $N_{match}=2$ Throw away

soft single-logarithmic double counting





Event matched, $N_{jet}>N_{part}$, keep for inclusive sample, but throw away for exclusive samples.